LBL-11353
LA-8520-M

DOE-2

ENGINEERS MANUAL

Version 2.1A

Energy and Environment Division
Building Energy Simulation Group
Lawrence Berkeley Laboratory
University of California
Berkeley, CA 94720

and

Group Q-11, Solar Energy Group, Energy Division
Los Alamos National Laboratory
Los Alamos, NM 87545

November 1982

Supported by the Office of Buildings and Community Systems
Assistant Secretary for Conservation and Renewable Energy
United States Department of Energy

Lawrence Berkeley
Laboratory

Los Alamos
Los Alamos National Laboratory
Los Alamos, New Mexico 87545

Prepared for the U.S. Department of Energy under Contract DE-AC03-76SF00098

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Edited by Don A. York and Charlene C. Cappiello
November 1, 1981

This work was supported by the Assistant Secretary for Conservation and Renewable Energy, Office of Buildings and Community Systems, Buildings Division of the U.S. Department of Energy under Contract DE-AC03-76SF00098 (LBL), and by the U.S. Department of Energy under Contract W-7405-ENG-36 (LANL).

NOTICE

The explicit function of this computer program is to aid in the analysis of energy consumption of buildings. This program is not intended to be the sole source of information relied upon for the design of buildings. The basic authority that should be relied upon is the judgment and experience of the architect/engineer.

The technical information in this computer program has been compiled from the best available sources and is believed to be correct. Many of the equations and much of the methodology used by the DOE-2 computer program is based on the algorithms published by the American Society of Heating, Refrigerating, and Air Conditioning Engineers, Inc. (ASHRAE). However, this edition of the Engineers Manual does not reflect ASHRAE review comment.

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No references may be made to the DOE-2 computer program as having been responsible for calculations unless a complete, up-to-date copy of this program is used to perform the calculations and that copy has been certified by the DOE-2 staff as distributed through the DOE/National Energy Software Center at Argonne National Laboratory.

USER EVALUATION

DOE-2 ENGINEERS MANUAL

The editors of the DOE-2 Engineers Manual would appreciate your comments as a user of the manual. Please take a few minutes to answer these questions and return this sheet to Bruce D. Hunn, Los Alamos National Laboratory, Group Q-11, MS K571, P.O. Box 1663, Los Alamos, NM 87545 (telephone: commercial (505) 667-6441; FTS 843-6441).

1. Are you, as a user of this manual, serving as ___ an engineer, ___ a computer programmer, ___ other ______________________________________?

   Do you find that the manual contains

   ___ too much ___ not enough ___ the right amount

   of engineering detail?

   ___ too much ___ not enough ___ the right amount

   of program detail?

2. What is the date of the last revision to your manual? ________________

3. Does the manual largely provide the information you need?

   ___ yes ___ no ___ partially

   If your answer is not "yes," would you briefly describe the information you find lacking?

4. If you feel that the organization, format, or presentation clarity could be improved, what suggestions can you give us?

5. Have you found any errors? If so, would you please indicate them.

Error in Chapter ________, page ________

Nature of error:

Chapter ________, page ________

Nature of error:

Please feel free to continue your comments below. Thank you.

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ABSTRACT

The document describes the DOE-2 computer program, which is capable of rapid and detailed analysis of energy consumption in buildings. A new user-oriented input language, named the Building Description Language (BDL), has been written to allow simplified manipulation of the many variables used to describe a building and its operation.

This Engineers Manual provides the user with information necessary to understand in detail the DOE-2 computer program. It contains a summary of the equations and algorithms used to perform the calculations. The operation, structure, and logical sequence of calculations is described in a step-by-step manner for each of the major computational programs.

The computer program described in this manual includes:

1. The BDL Processor that will analyze the input instructions, execute computer system control commands, perform assignments and data retrieval, and control the operation of the LOADS, SYSTEMS, PLANT, ECONOMICS, and REPORT programs.

2. The LOADS simulator that calculates peak (design) zone loads, hourly loads, the effect of the ambient weather conditions, the occupancy, lighting, and equipment within the building, as well as variations in the size, shape, location, orientation, and construction of walls, roofs, floors, fenestrations, and attachments (awnings, balconies) of a building.

3. A Heating, Ventilating, and Air-Conditioning (HVAC) SYSTEMS simulator that is capable of modeling the operation of HVAC components including fans, coils, economizers, humidifiers, etc., arranged in 1 of 21 standard configurations and operated according to various temperature, ventilation, and humidity control strategies.

4. A PLANT equipment simulator that models the operation of boilers, chillers, electrical generation equipment, heating and storage apparatus, and solar heating and/or cooling systems.

5. An ECONOMICS simulation program that calculates life-cycle costs.

6. A REPORT program that produces either preformatted reports or reports of user-selected variables arranged according to user-specified formats.

7. A set of WEATHER programs capable of manipulating, summarizing, and plotting weather data.

A computer readable library of weather data has been prepared that includes temperature, wind, and cloud data for 60 locations in the United States. These data are used to calculate the response of a building for each hour of a year (8760 hr/yr). Examples of typical schedule data have also been prepared that allow hourly, daily, weekly, monthly, seasonal, and yearly

specifications of the building operation. These schedules are used to specify desired temperature variations, occupancy patterns, lighting schedules, and equipment operation schedules. A computer-readable library contains data on the thermal properties of walls, roofs, floors, windows, doors, and attachments. The user is allowed to create new library entries using his own data and/or to select and assemble data for each specific job.

One feature of the DOE-2 computer program that cannot be over emphasized is its potential for optimizing energy utilization, or in other words, maximizing energy conservation. Once a building has been successfully simulated, the user can study energy consumption by conducting parametric computer runs in which one or more building parameters (insulation thickness, glass type, lighting type, etc.) are changed by the user and all other parameters remain the same (but do not have to be respecified for each parametric run). Likewise, the output from one simulator may be saved and be used as input for many versions of the following simulator. Logically, a parametric run can be justified, from a cost standpoint, if the payback over the life of the building is equal to or greater than the cost of the parametric run.

ACKNOWLEDGMENTS

This Engineers Manual was prepared by Group Q-11, Solar Energy Group, Energy Division, Los Alamos National Laboratory and the Building Energy Simulation Group, Lawrence Berkeley Laboratory (LBL). It was a joint effort of the following people:

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Weighting Factors Calculations:	Jerry F. Kerrisk
Curve Fit:	W. Frederick Buhl
LOADS Simulator:	W. Frederick Buhl
Shadow Calculations:	Metin Lokmanhekim
SYSTEMS Simulator:	James J. Hirsch
PLANT Simulator:	Steven D. Gates and Stephen C. Choi
CBS (Solar Simulator):	Norman M. Schnurr
ECONOMICS Simulator:	Frederick C. Winkelmann

The DOE-2 computer program described by this Engineers Manual is the result of participation and cooperation of many persons. The combined efforts of many different laboratories, private companies, and individuals were essential to the successful completion of this project. The participation of state and federal agencies, university personnel, representatives of professional societies, and many individual architects and engineers is gratefully acknowledged.

The following organizations and personnel have made significant contributions to produce DOE-2.

National Laboratories

LAWRENCE BERKELEY LABORATORY, Berkeley, California

LOS ALAMOS NATIONAL LABORATORY, Los Alamos, New Mexico

Principal Consultants

Metin Lokmanhekim, Ellicott City, Maryland
Ayres Associates, Los Angeles, California
Bruce E. Birdsall, Columbus, Ohio

Prime Contractor (Cal-ERDA and DOE-1 only)

Consultants Computation Bureau/Cumali Associates, Oakland, California
Zulfikar O. Cumali

Program Sponsor

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Office of the Assistant Secretary for Conservation and Solar Applications
Office of Buildings and Community Systems
Buildings Division
Washington, DC 20545

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The DOE-2 Building Description Language was created and designed by:

Mark A. Roschke, James J. Hirsch, and W. Frederick Buhl. (In addition, Zulfikar O. Cumali, A. Ender Erdem, Robert M. Graven, and Metin Lokmanhekim were instrumental in the conceptual development of the DOE-1 Building Description Language.)

The principal engineering/programming staff for DOE-2 included:

W. Frederick Buhl and Jerry F. Kerrisk (LOADS), Steven D. Gates and Stephen C. Choi (PLANT), James J. Hirsch (SYSTEMS), Mark A. Roschke (CBS Solar Simulator), and Frederick C. Winkelmann (ECONOMICS and LOADS). (In addition, Bruce E. Birdsall, Zulfikar O. Cumali, A. Ender Erdem, and Metin Lokmanhekim were instrumental in the development of the concepts used in the programs. Paul K. Davis, Jerry J. Kaganove, and Roy L. Smith were also included in the DOE-1 engineering/programming staff.)

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Finally, the editors of the 2.1A Version of the Engineer's Manual would like to thank Charlene J. McHale for the word processing of this manual.

STATUS - MAY 1981

This edition of the DOE-2 Engineers Manual describes version 2.1A of the DOE-2 program code and replaces the DOE-2.0 Program Manual of February 15, 1979.

The DOE-2 program will operate on any Control Data Corporation (CDC) computer with a FTN4 compiler or any International Business Machine (IBM) computer with a Level G compiler, or better.

The DOE-2 computer program is available from the:

National Technical Information Service (NTIS)
U.S. Department of Commerce
5285 Port Royal Road
Springfield, Virginia 22161

Telephone: Commercial (703) 487-4650 or FTS 737-4650

To obtain a copy of the computer program tape and/or the documentation package ask for:

	NTIS No.		
	DOE-2.0A	DOE-2.1	DOE-2.1A
Program Tape (CDC)	PB-292 250	PB80-148398	PB81-152456
Program Tape (IBM)	--	PB80-215940	PB81-183212
Documentation Package	PB-292 251 (3 volumes)	PB80-148380 (3 volumes, one) of which is in two parts)	PB81-152464 (4 volumes, one of which is in two parts)

Interested persons should write or call NTIS for more detailed ordering information, including current price.

DOE-2 is installed and operating at Lawrence Berkeley Laboratory on a CDC 6600/7600. Any DOE contractor may access it through the Lawrence Berkeley Laboratory remote users network. DOE users may contact:

DOE-2 User Coordination Office
Lawrence Berkeley Laboratory
Building 90, Room 3147
Berkeley, California 94720
Telephone: Commercial (415) 486-5711 or FTS 451-5711

A document entitled "Using DOE-2.1 at Lawrence Berkeley Laboratory" is available.

Additional versions of DOE-2 are available at the Los Alamos National Laboratory in Los Alamos, New Mexico, for in-house use by Los Alamos National Laboratory personnel.

Any individual in the private sector who is interested in using DOE-2 is urged to investigate its availability through one of the computer service bureaus or consultants. As of March 1, 1981, the following computer service firms are expected to offer the program for private use. For information about the status of such plans, contact:

SERVICE BUREAU	CONTACT
CALIFORNIA Berkeley Solar Group 3140 Grove St. Berkeley, CA 94703	Grace Prez Commerical - (415) 843-7600 FTS - 8-415-843-7600
COLORADO Computer Sharing Services, Inc. 7535 East Hampdon Avenue, Suite 200 Denver, Colorado 80231	Tom Rallens, Customer Service Commercial - (303) 695-1500 FTS - 8-303-695-1500
Martin-Marietta Data Systems P. O. Box 179 Mail Stop I4100 Denver, Colorado 80201	O. Michael Antoun (Los Angeles) Commercial - (213) 552-9541 FTS - 8-213-552-9541
CONNECTICUT Arga Associates 1056 Chapel Street New Haven, Conn. 06510	Dr. Robert Frew, Consultant Commercial - (203) 789-0555 FTS Op 8-244-2000 IBM ONLY
KANSAS United Computing Systems, Inc. P. O. Box 8551 Kansas City, Kan. 64114	John C. Hicks Commercial - (913) 341-9161 FTS - 8-913-341-9161
MASSACHUSETTS University of Massachusetts Dept. of Mechanical Engineering Amhurst, Mass. 01003	Lawrence L. Ambs Associate Professor Commercial - (413)-545-0949 FTS - 8-413-545-0949 (University and local govt. clients only)
MICHIGAN Airflow Science Corporation/BACS, Inc. 352 North Main Street Plymouth, Michigan 48170	James C. Paul Coordinator of DOE-2 User Services Commercial - (313) 459-4000 FTS 8-313-459-4000 (Michigan area only)
MINNESOTA Cybernet User Service Control Data Corporation P. O. Box "O" Minneapolis, Minn. 55440	Jim Nail Mail Code HQW-05G Commercial - (612) 853-8858 FTS Op 8-725-4242

SERVICE BUREAU	CONTACT
MISSOURI McDonnell-Douglas Automation Co. P. O. Box 516 St. Louis, Mo. 63166	Charles Whitman Dept. K-242 Commercial - (314) 232-8570 FTS Op 8-279-4110
VIRGINIA Babcock and Wilcox P. O. Box 1260 Lynchburg, Va. 24505	Jim Lynch Commercial - (804) 384-5111 x 2081 FTS Op 8-937-6011
WASHINGTON Boeing Computer Services Co. P. O. Box 24346, M. S. 9C-02 Seattle, Wash. 98124	David W. Halstead Commercial - (206) 575-5009 FTS - 8-206-575-5009

I. INTRODUCTION

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I. INTRODUCTION

This Engineers Manual describes the philosophy of the DOE-2 computer program. The algorithms used are described in detail in Chapters III, IV, V, and VI. This manual provides the information required for understanding "what happens to the input data" to the DOE-2 computer program. This manual is written for the engineer/architect/analyst who is a user of the code. Although this manual will contain occasional references to subroutine names and variable names, it has been compiled so that it is not necessary for a user to have a listing of the computer code. The subroutine names and variable names are intended for those persons who intend to maintain or modify the code.

This manual is produced in loose-leaf notebook form, so that it can be readily updated and expanded by the substitution of revised pages and the addition of new ones.

The user should not be overwhelmed, or overly concerned, by the size of this manual. Although the information is rather voluminous, the user will address only these portions of the manual that deal with the problem at hand. It is neither necessary nor recommended that the user read this manual in its entirety because most of the material will be irrelevant to the user's problem. The user should familarize himself with the organization of this manual so that he can locate the answer to problems, if and when they arise.

The remainder of this first chapter contains a brief discussion of the documentation and source code of the DOE-2 program, and summaries of the major computer subprograms.

1. DOCUMENTATION

1.1 Volume I - Users Guide/BDL Summary

BDL Summary - This document provides a summary of all commands, keywords, and code-words in the Building Description Language.

Users Guide - This guide explains the philosophy and interpretation of the DOE-2 code along with annotated examples.

1.2 Volume II - Sample Run Book

In this document are found numerous computer example runs which display both input data and output data.

1.3 Volume III - Reference Manual (Parts 1 and 2) (Ref.1)

This manual presents detailed step-by-step instructions on "how to input data" to the DOE-2 program.

1.4 Volume IV - Engineers Manual

This manual, as stated earlier, provides the information needed for understanding "what happens to the input data" to the DOE-2 computer program. It contains a summary of the equations and algorithms used to perform the calculations. The relationship of the DOE-2 algorithms to ASHRAE algorithms is also given and is traced to the ASHRAE documentation.

1.5. Site Manuals

In addition, further user guidance is available in Site Manuals, which provide the necessary information for the use of DOE-2 at specific computing installations. These manuals are not provided by the National Technical Information Service, but rather are available from the computing installations.

2. PROGRAM PACKAGE

The DOE-2 program package for CDC and IBM computers is available in two parts:

(a) Magnetic tape (FORTRAN source) of the program and auxiliary routines with control/run information, sample problem decks, and weather file library data plus

(b) Printed documentation.

Listings of DOE-2 are available from the National Energy Software Center. If any problems arise with the magnetic tape copy, assistance is available by telephoning the Center. Punched card copies of the program are not available, because the program is too large.

3. SUMMARY OF PROGRAM

DOE-2 enables architects and engineers to compute energy consumption in buildings. The program can simulate hour-by-hour performance of a building for each of the 8760 hours in a year. A new computer language, the Building Description Language, has been written. It is a computer language for analysis of building energy consumption that permits the user to instruct a computer in familiar English terminology.

Building Description Language has been developed primarily to aid engineers and architects in the difficult and time-consuming task of designing energy-efficient buildings that have low life-cycle cost. The energy consumption of a building is determined by its shape; the thermal properties of materials; the size and position of walls, floors, roofs, windows, and doors; and the transient effects of shading, occupancy patterns, lighting schedules, equipment operation, ambient conditions, and temperature and humidity controls. Energy consumption is affected, also, by the operation of primary and secondary HVAC systems and by the type and efficiency of the fuel conversion (plant) equipment. Furthermore, the life-cycle cost of operating a building under different economic constraints can strongly influence basic design decisions.

DOE-2 also provides a means of performing the complicated analysis of energy consumption without the necessity of instructing the program correctly in every minor detail. A set of default values (numbers used for the value of a variable if the user does not assign one) is included to reduce the amount of input that must be supplied in order to run the program.

Figure I.1 shows a brief organizational outline of the DOE-2 computer program.

3.1 Program Control

DOE-2 consists of more than 30 files, not including the weather data. Hence, assuring that the subprograms are properly executed requires a substantial number of bookkeeping functions, which are performed by a sequence of job control instructions. The job control instructions are unique to each site, because they interact with the particular operating system in use at that site. The user should contact a consultant at his computing site for more information.

3.2 BDL Processor

The BDL Processor sequentially checks each BDL instruction for proper form, syntax, and content. The BDL Processor also checks for values that are beyond the expected range for input variables. As stated before, if a value is not specified, the BDL processor assigns an assumed (default) value, which will appear in the listing of input data. Sometimes the default value is actually a set of default values, such as a performance curve for a piece of equipment. It is possible for the user to override this set of default values (performance curve) with a different set of default values. The BDL Processor also collects whatever data the user desires from the various permanent libraries, e.g., data from the Materials Library. Response factors, numbers that are used to determine the transient (or "dynamic") flow of heat through exterior walls and roofs as they react to randomly fluctuating climatic conditions, are also calculated by the BDL Processor for use by the LOADS and SYSTEMS programs. The BDL processor will calculate, if desired, Custom Weighting Factors and build user-designed libraries of materials and walls. These factors are intended to account for the thermal lag in the heating and cooling of furnishings and structures. The BDL Processor also prepares the input data files for use by the LOADS, SYSTEMS, PLANT, or ECONOMICS (LSPE) simulators.

It is important to recognize that each of the LSPE simulators depends on the results of some or all of the previous simulators, and that many variations and combinations are allowed. Each of the LSPE simulators can be run repeatedly, to study the effect of design variations. Superior energy-efficient building design can result in greatly reduced energy consumption and significantly lower life-cycle cost.

3.3 LOADS Program

The LOADS program (simulator) calculates the hourly heating and cooling loads, using the algorithms described in this manual.

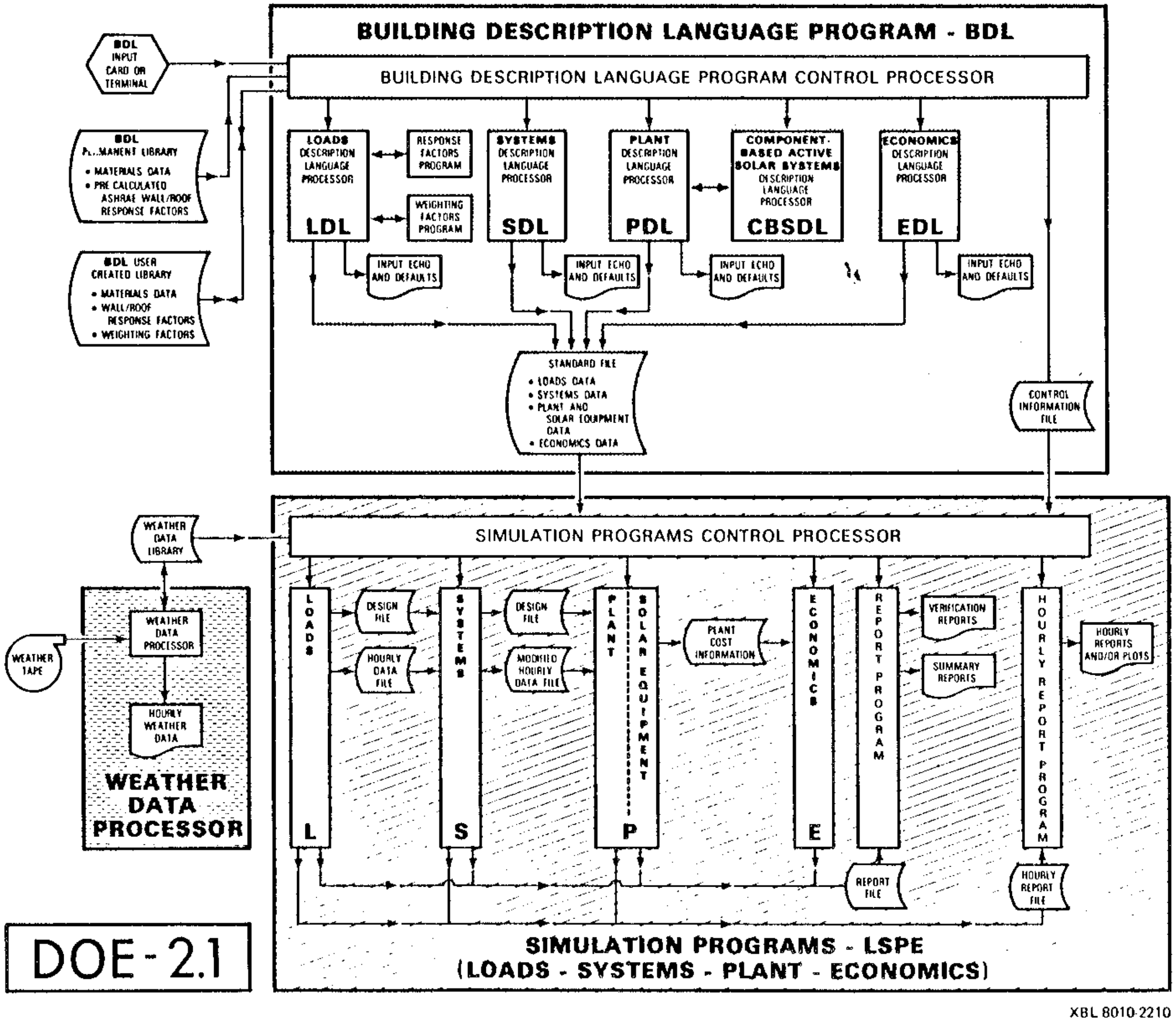

Fig. I.1. DOE-2 computer ·rogram configuration.

In the LOADS program, the heat gains and losses through walls, roofs, floors, windows, and doors are calculated separately. Heat transfer by conduction and radiation through the building skin is computed, using the response factors generated in BDL. The weighting factors, also generated in BDL, consider the effects of the thermal mass, placement of insulation, sun angle, cloud cover, and building location, orientation, and architectural features. Every set of weighting factors generated is placed in a file to be used by the LOADS and SYSTEMS programs. Infiltration loads can be calculated on the basis of the difference between the inside and outside conditions and on an assumed leak rate (crack method) or by an air-change method.

Internal use of energy for lighting and equipment is also computed according to schedules assigned by the user for each piece of equipment that affects the energy balance of each space. The latent and sensible heat given off by the building occupants is calculated as an hour-by-hour function of the occupancy of the building.

All the LOADS computations are performed on the basis of a fixed temperature for each space as specified by the user. Because the LOADS program calculates thermal loads not on the basis of hourly weather data but artificial (fixed) space temperatures, the output may have little bearing on the actual thermal requirements of a building. It is, instead, a baseline profile of the thermal performance of a space, given a fixed internal temperature. The SYSTEMS program then modifies the output of the LOADS program, to produce actual thermal loads based on a hourly variable internal temperature.

The output of LOADS is useful to architects who wish to examine the thermal behavior of various combinations of materials used to make up alternative exterior walls and roofs. However, it is expected that engineers will be interested in the predicted thermal demands on the physical plant (chillers and heaters), obtained by running both the LOADS and SYSTEMS programs.

3.4 SYSTEMS Program

The SYSTEMS program contains algorithms for simulating performance of the secondary HVAC equipment used to control the temperature and humidity of each zone within the building. Many of the equations used to develop the SYSTEMS simulation procedure are given in Refs. 2 and 3. These algorithms have been organized and coded to allow selection of one of the preprogrammed space conditioning systems described in Chap. IV. The SYSTEMS program is used by choosing one of these preprogrammed systems and providing the necessary input data for the simulation calculations.

The SYSTEMS program uses the output information from the LOADS program and a list of user-defined system characteristics (e.g., air flow rates, thermostat settings, schedules of equipment operation, or temperature setback schedules) to calculate the hour-by-hour energy requirements of the secondary HVAC system. The SYSTEMS program then recalculates the thermal loads (originally calculated in the LOADS program), based on variable temperature conditions for each zone.

3.5 PLANT Program

The PLANT program contains the equations necessary to calculate the performance of the primary energy conversion equipment. The operation of each plant component (e.g., boiler, absorption chiller, compression chiller, cooling tower, hot water storage tank, solar heater) is modeled on the basis of operating conditions and part-load performance characteristics. The user selects the type of plant equipment to be modeled (e.g., 2-stage absorption chiller), the size of each unit (e.g., 100 tons), the number of units, and the number of units simultaneously available. Values for equipment lifetime and maintenance may also be entered if preprogrammed (default) values for these variables are not used. The sequence of equipment operation may be specified as a step function (e.g., from 0 to 500,000 Btu/hr, unit 1; from 500,001 to 10M Btu/hr, units 1 and 2). The user may schedule equipment operation by time (hourly or seasonally) or by peak load schedules. Additionally, the operating strategy between the various types of equipment may be specified. Energy storage may be specified. The PLANT program uses hourly results from the LOADS and SYSTEMS programs and the user's instructions to calculate the electrical and thermal energy consumption of the building. The DOE-2 PLANT program also contains subroutines for computing the life-cycle costs of plant equipment.

3.6 ECONOMICS Program

The ECONOMICS program may be used to compute the life-cycle costs of various building components and to generate investment statistics for economic comparison of alternative projects. The methodology used is similar to that recommended by DOE for evaluation of proposed energy conservation projects (Ref. 3).

3.7 REPORT Program

A REPORT program is used to collect information from the output files of the LSPE programs. The output data are then arranged in lists or tables according to the format of a standard output report. If a user wishes to examine a particular variable that is not available in a standard output report, he may select the variable and print its hourly values through the REPORT program.

3.8 WEATHER Files and Programs

Weather data are accessed by using control card statements. The weather file contains Test Reference Year (TRY) data for the locations listed in Chap. VIII of the DOE-2 Reference Manual (Ref. 1), weather data for the National Laboratory sites, and data for various climate regions in California.

Manipulation of weather data is a separate activity, independent of the LSPE programs. Ordinary use of the LSPE programs to calculate the energy consumption of a building does not require use of the WEATHER analysis programs. The WEATHER analysis programs may be run to examine and prepare weather data not already in the DOE-2 file. Each meteorological variable may be changed or printed, and most may be plotted as desired, through these programs.

3.9 Libraries

Schedules Library data include graphs of various schedules that may be entered to calculate the hour-by-hour heat input to a space from lighting, equipment, or occupants. Various changes may be made in the schedule data, to customize it to particular requirements. Schedule data however are not machine readable.

Both the Materials Library and the Constructions Library are directly addressable by the DOE-2 program. The Materials Library contains data on the thermal properties of materials, to be used in the calculation of heat transfer through space boundaries. Thermal performance of a wall or roof may be modeled 1) by selecting and mathematically laminating various materials or 2) by specifying the desired construction from the Constructions Library by code-word. Each of the ASHRAE constructions is listed in Ref. 4. Other surfaces may be added by the user.

In summary, the DOE-2 library consists of machine-readable construction and materials data. Schedule data are available but are not machine-readable. Private data files may be created by the user for individual use.

4. CHAPTER I REFERENCES

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II. BUILDING DESCRIPTION LANGUAGE

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1. RESPONSE FACTORS
by W. Frederick Buhl and Richard B. Curtis

Note: This discussion of response factors is presented here in BDL because the calculation of response factors is actually part of BDL. The results of these calculations are, however, used later in LOADS.

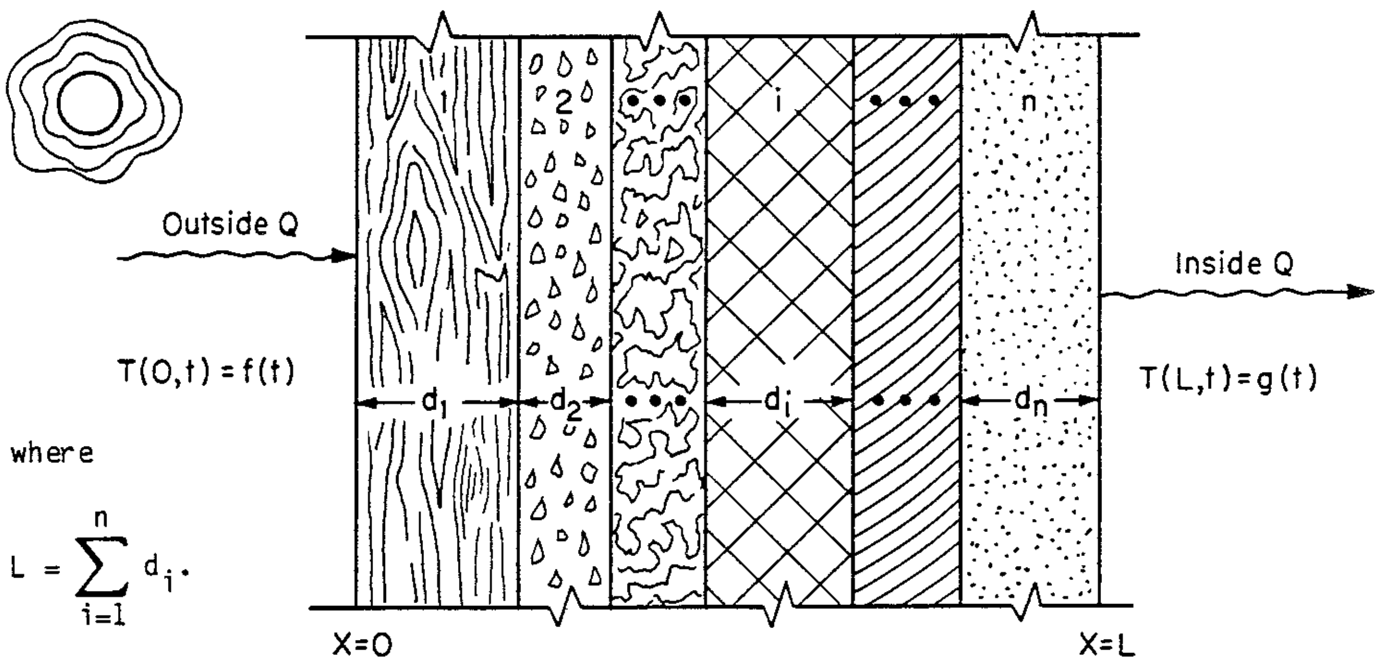
1.1 Theory

The problem is to find the heat flux at the inside and outside surfaces of a wall, given the temperature of the inside and outside surfaces. One-dimensional heat flow will be assumed. The approach is to solve the one-dimensional diffusion equation

$$\frac{\partial^2 T}{\partial x^2} = \frac{1}{\alpha}\frac{\partial T}{\partial t} \tag{II.1}$$

where
T = temperature
x = distance from the outside surface
t = time
α = diffusivity = $k/c\rho$
k = thermal conductivity
c = specific heat, and
ρ = density.

The wall is made up of layers in the following fashion



where

$$L = \sum_{i=1}^{n} d_i .$$

Fig. II.1. Flow of energy through a wall of multiple layers.

The strategy is to solve Eq. (II.1) for a simple case and then build the solution to the more complicated case from the simple case. For instance, a solution could be found for the case where the excitation functions are $f(t)$ = step function and $g(t) = 0$, and then approximate a more general $f(t)$ with a weighted sum of step functions. The solution would then be a weighted sum of solutions to the simpler case. This technique of superimposing simple cases to build up a general solution is probably the most common technique used in solving partial differential equations. Often, the solution for an excitation function equal to a delta function is used. When the boundary conditions are

$$T(x,0) = f(x)$$

for an infinite solid, the solution for $f(x) = \delta(x)$ is the Green's function for the problem

$$G(x,t) = \sqrt{\frac{1}{4\pi\alpha t}}\, e^{-x2/4\alpha t}$$

and

$$T(x,t) = \int_{-\infty}^{\infty} G(x-x',t)\, f(x')\, dx'.$$

In the case shown in Fig. II.1, suppose there is only one layer with $d_1 = L$. If the solution for

$$f(t) = \delta(t),\ g(t) = 0$$

is obtained, the solution for a general $f(t)$ with $g(t) = 0$, can be obtained from

$$T(x,t) = \int_{0}^{t} f(t-\tau)\, K\,(x,\tau)\, d\tau\,, \qquad \text{(II.2)}$$

where $K(x,\tau)$ is the solution for $f(t) = \delta(t)$; i.e., it is the response function for a delta function input. The integral in Eq. (II.2) is called a convolution integral, or Duhamel's formula.

In building energy analysis, temperature information is not known for g(t) and f(t) in the form of a continuous function. Rather, outside temperature is usually available at one hour intervals. It is convenient, therefore, to use a rectangular pulse or a triangular pulse for the excitation, rather than a delta function. Because it is assumed that g(t), the outside temperature, is a smooth function (continuous derivatives) even though data are only available at hourly intervals, it is best to use overlapping triangular pulses rather than rectangular, because triangular pulses can more easily approximate a smooth function, as is illustrated in the following figures.

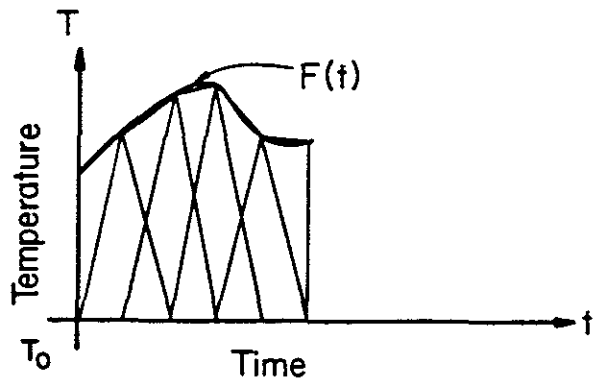


Fig. II.2. Overlapping triangular pulses defining a function.

A series of response factors are obtained by sampling the response function to a triangular excitation at equal time intervals - in this case, hourly intervals. The response factors that will be used are the heat flux responses to a temperature excitation. The X response factor series represents the response (the heat flow out of the outside surface) at x = 0 to a triangular temperature excitation at x = 0. The Z response factor series represents the response (heat flow out of the inside surface) at x = L to a triangular excitation in temperature at x = L. The Y response factor series is the response (heat flux out of the inside surface) at x = L to a triangular temperature pulse at x = 0 (the outside surface).

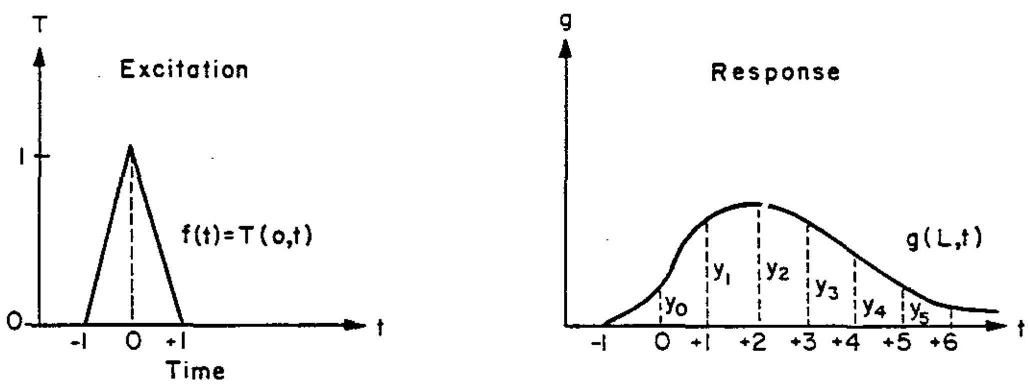


Fig. II.3. Definition of Y response factors.

The first step, in solving the situation depicted in Fig. II.1, is to obtain a solution for the one layer case ($n = 1$) with $f(t) = 0$. Solution will be via the Laplace transform method. Although this is not necessary for $n = 1$, it will be vital for obtaining solutions with $n > 1$. The Laplace transformed diffusion equation is

$$s\, T(x,s) = \alpha \frac{\partial^2 T(x,s)}{\partial x^2} \qquad \text{(II.3)}$$

and the boundary conditions are

$$T(0,s) = 0 \qquad\qquad T(d_1,s) = g(s). \qquad \text{(II.4)}$$

Assume $g(t) = 0$ for $t \leq 0$.

A solution is

$$T(x,s) = g(s) \frac{\sinh\,(x\sqrt{s/\alpha_1})}{\sinh\,(d_1\sqrt{s/\alpha_1})} .$$

$$\phi_{T1}(x,s) = \frac{\sinh\,(x\sqrt{s/\alpha_1})}{\sinh\,(d_1\sqrt{s/\alpha_1})} \qquad \text{(II.5)}$$

is known as a transfer function. It relates the input or excitation $g(s)$ to the output or response $T(x,s)$ in s space. Here, the subscript T denotes that this is the transfer function relating temperature excitation to temperature response, and the 1 indicates that the response was at $x = d_1$. $\phi_{T1}(x,s)$ is the response to a delta function input; that is, $g(t) = \delta(t)$, $g(s) = 1$. The corresponding heat flux transfer function is

$$\phi_{q1}(x,s) = -k_1 \frac{\partial\, \phi_{T1}\,(x,s)}{\partial x} = -k_1\sqrt{s/\alpha_1}\, \frac{\cosh\,(x\sqrt{s/\alpha_1})}{\sinh\left[d_1\,\sqrt{s/\alpha_1}\right]} . \qquad \text{(II.6)}$$

The complementary boundary value problem will now be solved.

$T(d_1,x) = g(t) = 0 \qquad\qquad T(0,x) = f(t)$

or

$T(0,s) = f(s) \qquad\qquad T(d_1,s) = 0,$

then

$$T(x,s) = f(s)\ \frac{\sinh\left[(d_1 - x)\sqrt{s/\alpha_1}\right]}{\sinh\left(d_1\sqrt{s/\alpha_1}\right)}$$

$$\phi_{T0}(x,s) = \frac{\sinh\left[(d_1 - x)\sqrt{s/d_1}\right]}{\sinh\left(d_1\sqrt{s/\alpha_1}\right)}$$

$$\phi_{q0}(x,s) = -k_1\ \frac{\partial\ \phi_{T0}(x,s)}{\partial x}$$

$$= k_1\sqrt{s/\alpha_1}\ \ \frac{\cosh\left[(d_1 - x)\sqrt{s/\alpha_1}\right]}{\sinh\left(d_1\sqrt{s/\alpha_1}\right)}\ . \tag{II.7}$$

Note that $\phi_{q0}(d_1,s) = -\phi_{q1}(0,s)$, and
$\phi_{q0}(0,s) = -\phi_{q1}(d_1,s)$.

In general, in s space, it can be written

output = (transfer function) (input), or
$O(s) = K(s)\ I(s)$.

From Eq. (II.6), the heat flux output at $x = 0$, caused by temperature input at $x = d_1$, is

$$q(0,s) = \phi_{q1}\ (0,s)\ T(d_1,s).$$

The heat flux at $x = 0$, caused by temperature input at $x = 0$, is

$$q(0,s) = \phi_{q0}(0,s)\ T(0,s).$$

It is possible to combine the two previous expressions to obtain the heat flux at $x = 0$, which is caused by temperature excitation of both $x = 0$ and $x = d_1$,

$$q(0,s) = \phi_{q0}\,(0,s)\;T(0,s) + \phi_{q1}(0,s)\;T(d_1,s). \tag{II.8}$$

Similarly, heat flux at $x = d_1$ is

$$q(d_1,s) = \phi_{q0}\,(d_1,s)\;T(0,s) + \phi_{q1}\;T(d_1,s)\;T(d_1,s). \tag{II.9}$$

The multiplication of two functions in s space becomes a convolution in t space. Thus, in t space,

$$q(0,t) = \int_0^\infty \phi_{q0}\,(0,\tau)\;T(0,t-\tau)\;d\tau + \int_0^\infty \phi_{q1}\,(0,\tau)\;T(d_1,t-\tau)\;d\tau$$

$$q(d_1,t) = \int_0^\infty \phi_{q0}\,(d_1,\tau)\;T(0,t-\tau)\;d\tau + \int_0^\infty \phi_{q1}\,(d_1,\tau)\;T(d_1,t-\tau)\;d\tau. \tag{II.10}$$

Equations. (II.8) and (II.9) can be written in matrix notation ,

$$\begin{bmatrix} q(0,s) \\ q(d_1,s) \end{bmatrix} = \begin{bmatrix} \phi_{q0}(0,s) & \phi_{q1}(0,s) \\ \phi_{q0}(d_1,s) & \phi_{q1}(d_1,s) \end{bmatrix} \begin{bmatrix} T(0,s) \\ T(d_1,s) \end{bmatrix}. \tag{II.11}$$

To handle the n layer problem, it is necessary to rearrange this so that q and T at $x = 0$, are on the same side of the equal sign. A new transfer matrix is defined

$$\begin{bmatrix} T(0,s) \\ q(0,s) \end{bmatrix} = \begin{bmatrix} A_1(s) & B_1(s) \\ C_1(s) & D_1(s) \end{bmatrix} \begin{bmatrix} T(d_1,s) \\ q(d_1,s) \end{bmatrix}. \tag{II.12}$$

This gives the response in temperature and heat flux at $x = 0$, caused by an excitation in temperature and heat flux at $x = d_1$.

Solving for A, B, C, and D yields

$$A_1(s) = -\frac{\phi_{q1}(d_1,s)}{\phi_{q0}(d_1,s)} = \cosh\ (d_1\sqrt{\alpha/d_1}),$$

$$B_1(s) = \frac{1}{\phi_{q0}(d_1,s)} = \frac{\sinh\ (d_1\sqrt{s/\alpha_1})}{k_1\sqrt{s/\alpha_1}},$$

$$C_1(s) = -\frac{\phi_{q0}(0,s)\ \phi_{q1}(d_1,s)}{\phi_{q0}\ (d_1,s)} + \phi_{q1}(0,s) = k_1\sqrt{s/\alpha_1}\ \sinh\ (d_1\sqrt{s/\alpha_1}),\ \text{and}$$

$$D_1(s) = \frac{\phi_{q0}(0,s)}{\phi_{q0}(d_1,s)} = \cosh\ (d_1\sqrt{s/\alpha_1}). \qquad \text{(II.13)}$$

Note that as the heat capacity of the layer goes to zero, $1/\alpha_1 \dashrightarrow 0$ and so

$$A(s) \dashrightarrow 1,\ B(s) \dashrightarrow \frac{d_1}{k_1} = R_1,\ C(s) \dashrightarrow 0,\ D(s) \dashrightarrow 1$$

$$\begin{bmatrix} A & B \\ C & D \end{bmatrix} \dashrightarrow \begin{bmatrix} 1 & R_1 \\ 0 & 1 \end{bmatrix}.$$

It is now possible to write down the n layer solution.

Because $\begin{bmatrix} T(0,s) \\ q(0,s) \end{bmatrix} = \begin{bmatrix} A_1 & B_1 \\ C_1 & D_1 \end{bmatrix} \begin{bmatrix} T(d_1,s) \\ q(d_1,s) \end{bmatrix}$

and $\begin{bmatrix} T(d_1,s) \\ q(d_1,s) \end{bmatrix} = \begin{bmatrix} A_2 & B_2 \\ C_2 & D_2 \end{bmatrix} \begin{bmatrix} T(d_2,s) \\ q(d_2,s) \end{bmatrix}$

then $\begin{bmatrix} T(0,s) \\ q(0,s) \end{bmatrix} = \begin{bmatrix} A_1 & C_1 \\ C_1 & D_1 \end{bmatrix} \begin{bmatrix} A_2 & C_2 \\ C_2 & D_2 \end{bmatrix} \begin{bmatrix} T(d_2,s) \\ q(d_2,s) \end{bmatrix}$

and for n layers

$$\begin{bmatrix} T(0,s) \\ q(0,s) \end{bmatrix} = \prod_{i=1}^{n} \begin{bmatrix} A_i(s) & C_i(s) \\ C_i(s) & D_i(s) \end{bmatrix} \begin{bmatrix} T(L,s) \\ q(L,s) \end{bmatrix} . \tag{II.14}$$

Defining $\begin{bmatrix} A(s) & B(s) \\ C(s) & D(s) \end{bmatrix} = \prod_{i=1}^{n} \begin{bmatrix} A_i & B_i \\ C_i & D_i \end{bmatrix}$,

then $\begin{bmatrix} T(0,s) \\ q(0,s) \end{bmatrix} = \begin{bmatrix} A(s) & B(s) \\ C(s) & D(s) \end{bmatrix} \begin{bmatrix} T(L,s) \\ q(L,s) \end{bmatrix}$.

Returning to the original form, with the heat fluxes given in terms of the temperatures,

$$\begin{bmatrix} q(0,s) \\ q(L,s) \end{bmatrix} = \begin{bmatrix} \frac{D(s)}{B(s)} & - \frac{1}{B(s)} \\ \frac{1}{B(s)} & - \frac{A(s)}{B(s)} \end{bmatrix} \begin{bmatrix} T(0,s) \\ T(L,s) \end{bmatrix}. \tag{II.15}$$

To obtain response factors, it is necessary to invert Eq. (II.15), letting T(0,t) and T(L,t) be triangular pulses. For simplicity, let T(0,t) and T(L,t) be ramps:

$T(0,t) = T(L,t) = t$, and

$T(0,s) = T(L,s) = 1/s^2$.

The triangular pulse can be built up out of ramp functions as follows. Let the ramp function be denoted as R(t).

$R(t) = t$.

Let the width of the base of the triangular function be 2Δ. Denote the triangular function as Φ. Thus,

$\Phi(t) = 0$ for $-\infty < t \leq -\Delta$,

$\Phi(t) = \frac{1}{\Delta} R(t + \Delta)$ for $-\Delta < t \leq 0$,

$$\Phi(t) = \frac{1}{\Delta} R(t + \Delta) - \frac{2}{\Delta} R(t) \text{ for } 0 < t \leq \Delta, \text{ and}$$

$$\Phi(t) = \frac{1}{\Delta} R(t + \Delta) - \frac{2}{\Delta} R(t) + \frac{1}{\Delta} R(t - \Delta) \text{ for } \Delta < t. \qquad \text{(II.16)}$$

Thus, once the heat flux response to a ramp excitation is known, it is possible to obtain the heat flux response to a triangular pulse from a linear combination of the ramp responses.

Define

$$X_r(s) = \frac{D(s)}{B(s)} \frac{1}{s^2},$$

$$Y_r(s) = \frac{1}{B(s)} \frac{1}{s^2}, \text{ and} \qquad \text{(II.17)}$$

$$Z_r(s) = \frac{A(s)}{B(s)} \frac{1}{s^2}.$$

The r subscript stands for ramp. $X_r(s)$ is the heat flux response in s space at x = 0 to a ramp temperature input at x = 0. From its inverse

$$L^{-1}[X_r(s)] = X_r(t),$$

the ramp X response factors are obtained by sampling $X_r(t)$ at hourly intervals. The normal, triangular pulse response factors will then be obtained from a linear combination of the X_r response factors. Similarly, from $Y_r(s)$ the Y response factors will be obtained, and from $Z_r(s)$, the Z response factors.

It is necessary to invert $X_r(s)$, $Y_r(s)$, and $Z_r(s)$. Working with $X_r(s)$ as an example, the general inversion integral for Laplace transforms (Ref. 1) gives

$$L^{-1}[X_r(s)] = X_r(t) = \frac{1}{2\pi j} \lim_{\beta \to \infty} \int_{\gamma - j\beta}^{\gamma + j\beta} e^{zt} X_r(z)\, dz \qquad \text{(II.18)}$$

where γ and β are real, and z is s allowed to be complex. The integral is along a line parallel to the imaginary axis in the complex plane.

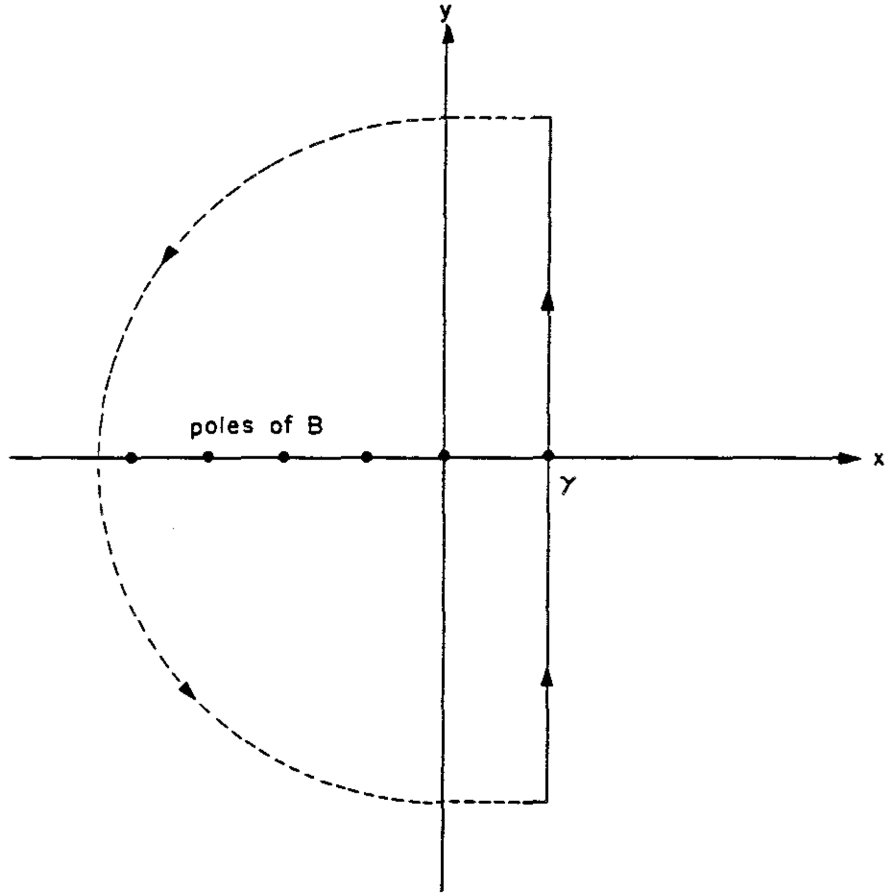


Fig. II.4. Contour of Inversion Integral.

This is formal inversion; there is no guarantee that it will work. According to Ref. 1, Page 178, the inversion will work if f(s) {f(s) = L[f(t)]} is analytic in the right half plane for x greater than some x_0, if f(s) is of the order s^{-k}, $k > 1$, and if f(x), $x \geq x_0$, is real. In our case, $D(s)/B(s) \propto \sqrt{s}$, so $X_r(s)$ [and $Y_r(s)$ and $Z_r(s)$] fall off quickly enough as $s \longrightarrow \infty$. From Eqs. (II.13) and (II.14), it can be seen that $X_r(s)$, $Y_r(s)$, and $Z_r(s)$ will be real for $x > 0$, $y = 0$. Clearly, $X_r(s)$ has a double pole at s = 0. In addition, for a single layer, $B_i(s)$ has zeros along the negative real axis. Let $s = -\beta$, then along the negative real axis

$$B_i(\beta) = \frac{\sin d_i\sqrt{\beta/\alpha_i}}{k_i\sqrt{\beta/\alpha_i}}$$

and B_i will have zeros at

$$d_i\sqrt{\beta/\alpha_i} = k\pi, \; k = 1,2,\ldots$$

or

$$\beta_k = \frac{\alpha_i^2 \, k^2 \, \pi^2}{d_i^2} \quad .$$

Thus, from Eqs. (II.13) and (II.14), it can be expected that $X_r(s)$, $Y_r(s)$, and $Z_r(s)$ will have double poles at $s = 0$, and poles along the negative real axis, but be analytic elsewhere.

The integral in Eq. (II.18) can be done by following the contour shown in Fig. II.4. The integrand will vanish along the semicircle, and

$$L^{-1}\,[X_r(s)] = \frac{1}{2\pi j}\, 2\pi j \sum_{k=1}^{\infty} [r_k(t)]$$

where r_k equals residue at the kth pole.

First, obtain the residue at $s = -\beta_k$. The integrand is

$$e^{st}\, \frac{1}{s^2}\, \frac{D(s)}{B(s)} \; .$$

Because $B(s) = 0$ at $s = -\beta_k$, $B(s)$ can be expanded:

$B(s) \dashrightarrow B(-\beta_k) + (s + \beta_k)\, B'(-\beta_k) + \ldots$

and as $s \dashrightarrow -\beta_k$, $B(s) \dashrightarrow (s + \beta_k)\, B'(-\beta_k)$.

The residue is

$$(s + \beta_k)\left[e^{st}\,\frac{1}{s^2}\,\frac{D(s)}{B(s)}\right]_{s\,=\,-\beta_k} = e^{-\beta_k t}\,\frac{1}{\beta_k^2}\left[\frac{D(s)}{B'(s)}\right]_{s\,=\,-\beta_k} .$$

At $s = 0$ a double pole exists, so the residue is

$$\frac{\partial}{\partial s}\left[s^2 e^{st}\frac{1}{s^2}\frac{D(s)}{B(s)}\right]_{s=0} = t\left[\frac{D(s)}{B(s)}\right]_{s=0} + \left[\frac{d}{ds}\ \frac{D(s)}{B(s)}\right]_{s=0} .$$

So

$$L^{-1}[X_r(s)] = t\left[\frac{D(s)}{B(s)}\right]_{s=0} + \frac{d}{ds}\left[\frac{D(s)}{B(s)}\right]_{s=0} + \sum_{k=1}^{\infty}\frac{1}{\beta_k^2}\ \frac{D(s)}{B'(s)}\Bigg|_{s=-\beta_k} e^{-\beta_k t} . \tag{II.19}$$

Because

$$\frac{d}{ds}\left[\frac{D(s)}{B(s)}\right] = \left[\frac{B\ \frac{dD}{ds} - \frac{dB}{ds}}{B^2}\right] , \tag{II.20}$$

and because the derivative of a product of matrices follows the same rule as the product of scalar functions, ..., i.e.,

$$[M] = \prod_{i=1}^{n}[M_i] \tag{II.21}$$

$$\left[\frac{dM}{ds}\right] = \sum_{m=1}^{n}\left(\prod_{i=1}^{m-1}[M_i]\right)\left[\frac{dM_m}{ds}\right]\left(\prod_{i=m+1}^{n}[M_i]\right) , \tag{II.22}$$

all that is needed to evaluate Eq. (II.19), in addition to the single layer matrix $[M_i]$, is

$$\lim_{s \to 0}[M_i],\ \lim_{s \to -\beta_k}[M_i],$$

$$\lim_{s \to 0}\ \frac{d}{ds}[M_i],\ \text{and}\ \lim_{s \to -\beta_k}\ \frac{d}{ds}[M_i]$$

$$[M_i(s)] = \begin{bmatrix} \cosh(d_i\sqrt{s/\alpha_i}) & \dfrac{\sinh(d_i\sqrt{s/\alpha_i})}{k_i\sqrt{s/\alpha_i}} \\ k_i\sqrt{s/\alpha_i}\ \sinh(d_i\sqrt{s/\alpha_i}) & \cosh(d_i\sqrt{s/\alpha_i}) \end{bmatrix} \qquad \text{(II.23)}$$

$$[M_i]_s = -\beta_k \begin{bmatrix} \cosh(d_i\sqrt{\beta_k/\alpha_i}) & \dfrac{\sin(d_i\sqrt{\beta_k/\alpha_i})}{k_i\sqrt{\beta_k/\alpha_i}} \\ -k_i\sqrt{\beta_k/\alpha_i}\ \sin(d_i\sqrt{\beta_k/\alpha_i}) & \cos(d_i\sqrt{\beta_k/\alpha_i}) \end{bmatrix} \qquad \text{(II.24)}$$

$$\frac{d}{ds}[M_i] = \begin{bmatrix} M'_{i1} & M'_{i2} \\ M'_{i3} & M'_{i4} \end{bmatrix}, \qquad \text{(II.25)}$$

where

$$M'_{i1} = M'_{i4} = \frac{1}{2}\ \frac{d_i}{\alpha_i}\ \frac{\sinh\left[d_i\sqrt{\frac{s}{\alpha_i}}\right]}{\sqrt{\frac{s}{\alpha_i}}} \quad ,$$

$$M'_{i2} = -\frac{1}{2}\frac{\sqrt{\alpha_i}}{k_i s^{\frac{3}{2}}} \sinh\left[d_i\sqrt{\frac{s}{\alpha_i}}\right] + \frac{1}{2}\frac{d_i}{k_i s} \cosh\left[d_i\sqrt{\frac{s}{\alpha_i}}\right],$$

$$M'_{i3} = \frac{1}{2}\frac{k_i}{\alpha_i}\frac{1}{\sqrt{\frac{s}{\alpha_i}}} \sinh\left[d_i\sqrt{\frac{s}{\alpha_i}}\right] + \frac{1}{2}\frac{k_i d_i}{\alpha_i} \cosh\left[d_i\sqrt{\frac{s}{\alpha_i}}\right],$$

$$[M_i]_{s=0} = \begin{bmatrix} 1 & \frac{d_i}{k_i} = R_i \\ 0 & 1 \end{bmatrix}, \qquad \text{(II.26)}$$

$$\frac{d}{ds}[M_i]_{s=0} = \frac{1}{2}\frac{d_i^2}{\alpha_i}\begin{bmatrix} 1 & \frac{1}{3}R_i \\ \frac{2}{R_i} & 1 \end{bmatrix}, \text{ and} \tag{II.27}$$

$$\frac{d}{ds}[M_i]\bigg|_{s=-\beta_k} = \begin{bmatrix} M'_{i1}\big|_{s=-\beta_k} & M'_{i2}\big|_{s=-\beta_k} \\ M'_{i3}\big|_{s=-\beta_k} & M'_{i4}\big|_{s=-\beta_k} \end{bmatrix}, \tag{II.28}$$

where

$$M'_{i1}\Big|_{s=-\beta_k} = M'_{i4}\Big|_{s=-\beta_k} = \frac{1}{2}\frac{d_i}{\alpha_i}\frac{\sin\left[d_i\sqrt{\frac{\beta_k}{\alpha_i}}\right]}{\sqrt{\frac{\beta_k}{\alpha_i}}},$$

$$M'_{i2}\Big|_{s=-\beta_k} = -\frac{1}{2}\frac{\sqrt{\alpha_i}}{k_i\beta_k^{\frac{3}{2}}}\sin\left[d_i\sqrt{\frac{\beta_k}{\alpha_i}}\right] - \frac{1}{2}\frac{d_i}{k_i\beta_i}\cos\left[d_i\sqrt{\frac{\beta_k}{\alpha_i}}\right], \text{ and}$$

$$M'_{i3}\Big|_{s=-\beta_k} = \frac{1}{2}\frac{k_i}{\alpha_i}\frac{1}{\sqrt{\frac{\beta_k}{\alpha_i}}}\sin\left[d_i\sqrt{\frac{\beta_k}{\alpha_i}}\right] + \frac{1}{2}\frac{k_i d_i}{\alpha_i}\cos\left[d_i\sqrt{\frac{\beta_k}{\alpha_i}}\right].$$

With these formulae, by finding the zeros of B(s), the inversion for any number of layers can be performed. The response or output functions $X_r(t)$, $Y_r(t)$, and $Z_r(t)$ for a ramp input $R(t) = t$ are now known. The ramp response factors X_{ri}, Y_{ri}, and Z_{ri} can be obtained by sampling $X_r(t)$, $Y_r(t)$, and $Z_r(t)$ at intervals of Δ. The response factors for a triangular pulse from Eq. (II.16) are

$$\begin{aligned} X_0 &= X_r(\Delta) \\ X_1 &= X_r(2\Delta) - 2X_r(\Delta) \\ X_i &= X_r[(i+1)\Delta] - 2X_r(i\Delta) + X_r[(i-1)\Delta]. \end{aligned} \tag{II.29}$$

Now, define

$$X_\delta(s) = \frac{D(s)}{B(s)},$$

$$Y_\delta(s) = \frac{1}{B(s)}\ , \text{ and}$$

$$Z_\delta(s) = \frac{A(s)}{B(s)}\ .$$

These are the response factors in s space to a δ function input; that is, they are the transfer functions. Then,

$$q(0,s) = X_\delta(s)\ T(0,s) - Y_\delta(s)\ T(L,s), \text{ and}$$

$$q(L,s) = Y_\delta(s)\ T(0,s) - Z_\delta(s)\ T(L,s).$$

So in t space

$$q(0,t) = \int_1^\infty X_\delta(\tau)\ T(0,t-\tau)d\tau - \int_1^\infty Y_\delta(\tau)\ T(L,t-\tau)d\tau, \text{ and}$$

$$q(L,t) = \int_0^\infty Y_\delta(\tau)\ T(0,t-\tau)d\tau - \int_0^\infty Z_\delta(\tau)\ T(L,t-\tau)d\tau.$$

For discrete time intervals, the continuous functions become time series. The integral turns into a summation, and the delta function excitation is replaced by the triangular pulse. The analagous equations are

$$q(0,t) = \sum_{i=0}^\infty X_i\ T(0,t - i\Delta) - \sum_{i=0}^\infty Y_i\ T(L,t - i\Delta), \text{ and}$$

$$(II.30)$$

$$q(L,t) = \sum_{i=0}^\infty Y_i T(0,t - i\Delta) - \sum_{i=0}^\infty Z_i\ T(L,t - i\Delta).$$

These are the fundamental equations for the use of response factors.

Equation (II.30) has summations running from zero to infinity. In actual practice, of course, the series is terminated when the terms become small enough to be neglected. Experience has shown, however, that often an inordinate number of terms must be kept to ensure sufficient accuracy. It is shown in another section of this chapter (Sec. II.2.2.2) how the response factors may be modified so that the series need only be taken out to the common ratio. The z-transform technique leads to the shortest possible series of the type given in Eq. (II.30).

The z-transform is discussed in considerable detail in the following section on weighting factors.

A time series is formed from a continuous function by sampling it at equal time intervals

$$f^*(t) = \sum_{i=0}^{\infty} f(i\Delta)\ \delta(t - i\Delta).$$

The Laplace transform of $f^*(t)$ is

$$L[f^*(t)] = f^*(s) = \sum_{i=0}^{\infty} f(i\Delta)\ e^{-i\Delta s}\ .$$

The z-transform is obtained by the variable substitution $z = e^{\Delta s}$, so

$$f^*(z) = \sum_{i=0}^{\infty} f(i\Delta)\ z^{-i}.$$

The z-transform is useful for systems for which the input is discrete. The z-transfer function can usually be obtained from the Laplace transfer function, as will shortly be seen.

Examine, for example, the heat flux response at one side of a slab to a temperature excitation on the other side. In s space

$$q(L,s) = Y_\delta(s)\ T(0,s)$$

where Y_δ is the transfer function. In z space

$$q^*(L,z) = K(z)\ T^*(0,z).$$

K(z), the transfer function, is most efficiently expressed as the ratio of two polynomials in z^{-1}

$$K(z) = \frac{N(z)}{D(z)} = \frac{a_0 + a_1 z^{-1} + a_2 z^{-2} + \ldots}{b_0 + b_1 z^{-1} + b_2 z^{-2} + \ldots}\ .$$

Thus,

$$q(L,0) + q(L,\Delta)z^{-1} + \ldots = \left[\frac{a_0 + a_1 z^{-1} + \ldots}{b_0 + b_1 z^{-1} + \ldots}\right][T(0,0) + T(0,\Delta)z^{-1} + \ldots\ .$$

By equating coefficients of powers of z, the following is obtained

$$q(L,n\Delta) = \frac{1}{b_0}\left[\sum_{i=0}^{n} a_i T[0,(n-i)\Delta] - \sum_{i=1}^{n} b_i q[L,(n-i)\Delta]\right]. \tag{II.31}$$

This should be compared to

$$q(L,t) = \sum_{i=0}^{\infty} Y_i\ T(0,t-i\Delta) \tag{II.32}$$

for response factors.

Notice that Eq. (II.31) involves past values of both the temperature and the heat flux, while the response factors summation involves past values of the temperature only. The reward for having to save past values of both temperature and heat flux will be that the coefficients a_i and b_i become small much faster than the response factors, and so fewer terms can be used to obtain the same accuracy.

The difference in form between Eqs. (II.31) and (II.32) is caused by the fact that K(z) was chosen to be the ratio of two polynomials. If K(z) had been chosen to be just a single polynomial, a form equivalent to Eq. (II.29) would have been obtained. In other words, the response factors are just a special case of the weighting factors.

One method of obtaining the z-transfer function is to first obtain the s or Laplace transfer function and from it obtain the z-transfer function. This is accomplished by choosing an input excitation function that has known s and z transforms, such as a ramp or step function (see Table II.1). The Laplace transform of the output is the Laplace transform of the input times the s transfer function. This output is converted to a function of z by variable substitution. Dividing the z-transform of the input by the output yields the z-transfer function.

Next, examine how this works for finding the z-transfer function corresponding to the example matrix element $D(s)/B(s) = X_\delta(s)$. The output corresponding to a ramp input was $1/s^2\ (D/B) = X_r(s)$. In Eq. (II.19) is found the inverse of $X_r(s)$. From Table II.1 it can be seen that $1/s^2\ D(s)/B(s)$ can be written as

$$X_r(s) = \frac{a}{s^2} + \frac{b}{s} + \sum_{i=1}^{\infty} \frac{C_i}{s + \beta_i} \qquad \text{(II.33)}$$

where $a = \frac{D(0)}{B(0)}$, $b = \frac{d}{ds}\left[\frac{D(s)}{B(s)}\right]_{s=0}$, and $C_n = \left[\frac{D(s)}{s^2\ B'(s)}\right]_{s=-\beta_n}$,

because this has the same inverse as

$$\frac{1}{s^2}\frac{D(s)}{B(s)} .$$

Using Table II.1, each term in Eq. (II.31) can be made into an equivalent z-transform.

$$O(z) = X_r(z) = \frac{a\Delta}{z(1-z^{-1})^2} + \frac{b}{1 - z^{-1}} + \sum_{i=1}^{\infty} \frac{C_i}{1 - \exp(-\beta_i\Delta)z^{-1}} .$$

Combining terms and dividing by

TABLE II.1

EQUIVALENT LAPLACE AND z-TRANSFORMS

f(t)	f(s)	f(z)
1	$\frac{1}{s}$	$\frac{1}{1 - z^{-1}}$
t	$\frac{1}{s^2}$	$\frac{\Delta}{z(1-z^{-1})^2}$
t^2	$\frac{2}{s^3}$	$\frac{\Delta^2(1+z^{-1})}{z(1-z^{-1})^3}$
e^{-at}	$\frac{1}{s+a}$	$\frac{1}{(1-e^{-a\Delta}z^{-1})}$

$$I(z) = \frac{\Delta}{z(1-z^{-1})^2} ,$$

a z-transfer function is obtained whose denominator is

$$D(z) = \prod_{i=1}^{\infty} [1 - \exp(\beta_i \ \Delta)z^{-1}]. \tag{II.34}$$

Equation (II.34) can be used to obtain the coefficient b_i of the denominator polynomial.

The a_i's, the numerator coefficients, can be obtained in several ways. The easiest way is as follows. From Eq. (II.19), X_{ri} can be obtained by evaluating $X_r(t)$ at $t = \Delta, 2\Delta, \ldots,$ etc. Because

$$O(z) = K(z)\ I(z) = \frac{N(z)}{D(z)}\ I(z),$$

then

$$N(z) = \frac{D(z)}{I(z)} O(z),$$

$$O(z) = X_r(z) = Y_{r0} + X_{r1}z^{-1} + X_{r2}z^{-2} + \dots ,$$

so

$$N(z) = \frac{z(1-z^{-1})^2}{\Delta} \prod_{i=1}^{\infty} (i-e^{-\beta_i\Delta}z^{-1}) \, (X_{r0} + X_{r1}z^{-1} + X_{r2}z^{-2} + \dots)$$

from which the a_i can be obtained.

The question must be answered of how large a root β_k must be in Eqs. (II.19) and (II.32) before it can be neglected. There is an infinite set of β_k's, and for complete accuracy, they should all be included. Denote the cutoff for roots as β_{max}. From Eq. (II.19) or (II.32) it can be seen that the contribution of β_{max} is at most $e^{-\beta_{max}\Delta}$. In DOE-2, $\beta_{max} = 30$, and with $\Delta = 1$ hour, terms of at most e^{-30} or approximately 10^{-13} are neglected.

The question of how fast weighting factors and response factors go to zero can now be answered. From Eq. (II.29) it can be seen that

$$b_n \propto \left[e^{-\beta_2\Delta}\right]\left[e^{-\beta_1\Delta}\right] \dots \left[e^{-\beta_n\Delta}\right]$$

where $\beta_1 < \beta_2 < \dots < \beta_n$.

From Eq. (II.19),

$$X_n \propto \left[e^{-\beta_1\Delta}\right]^n .$$

Thus, the weighting factors fall off much more quickly than the response factors.

1.2 Outline of Algorithm

Step 1

Let NL = number of layers, including the inside film resistance, if it is not equal to zero. The overall U-value for the wall is calculated:

$$U = \frac{1}{\left(\sum_{i=1}^{NL} R_i\right)} ,$$

$$R_i = \frac{d_i}{k_i} ,$$

where d_i = thickness of layers, and k_i = conductivity of layers.

If the layer has resistance only, R_i is set to the resistance the user has input in the MATERIAL or LAYERS instruction. U is called KO in the code.

Step 2

The necessary derivatives of the matrix elements A, B, and D at s = 0 are obtained. In particular, the quantities

$$K_1 = -\left| \frac{dB/ds}{B^2} \right|_{s=0}$$

$$M_1 = \left| \frac{dA(s)}{ds} \right|_{s=0} , \text{ and } M_4 = \left| \frac{dD(s)}{ds} \right|_{s=0}$$

are calculated using Eqs. (II.22), (II.26), and (II.27).

Steps 1 and 2 are performed in a call of subroutine ZERO.

Step 3

The first root of B greater than $\beta_{max} = -s = 30$ is obtained by a call to subroutine FALSE. This root is defined as ROOT(1) and is the first and largest number in what will be a sorted list of roots, β_k = ROOT(k), running from k = 1 to k = NROOT. Once the root is located, the quantities

$$B1 = D(s)\Big|_{s = -\beta_1}$$

$$B2 = A(s)\Big|_{s = -\beta_1}$$

$$BP3 = \frac{dB(s)}{ds}\Big|_{s = -\beta_1}$$

are calculated using Eqs. (II.21), (II.22), (II.24), and (II.25).

Step 4

Once the largest root that will be used is found, the program enters an iterative process to find all the roots of B(s) between 0 and the largest root.

A typical step can be described as follows. An interval slightly smaller than the interval (β_{k-1}, β_k) is defined

$$W1 = \beta_{k-1} + 10^{-5}/\Delta$$

$$W2 = \beta_k - 10^{-5}/\Delta.$$

A call to subroutine SLOPE answers the question of whether there is a root of B(s) in the interval (W1, W2).

If there is no root, the subroutine looks at the next lower interval $(\beta_{k-2}, \beta_{k-1})$.

If there is a root, a new interval (W1, W2') is defined in which the root resides, where W2' $\leq$ W2.

A call of subroutine FALSE then locates the root at W3 in (W1, W2') to an accuracy of 10^{-12} by a bisection technique. As in Step 3, the values

$$B1 = \Big|D(s)\Big|_{s = -W3}$$

$$B2 = \Big|A(s)\Big|_{s = -W3}$$

$$BP3 = \left|\frac{dB(s)}{ds}\right|_{s = -W3}$$

are calculated using Eqs. (II.21), (II.22), (II.24), and (II.25).

The root W3 is merged into a sorted list of roots β_i = ROOT(i), where $\beta_i < \beta_{i+1}$. Let $\{\beta_i\}$ denote the list before W3 is merged in, and $\{\beta_i'\}$ the list after W3 is merged in. Then,

$$\beta_{k-1} < W3 < \beta_k$$

and

$$\beta_i' = \beta_i \text{ for } 1 \leq i \leq k-1$$

$$\beta_k' = W3$$

$$\beta_{i+1}' = \beta_i \text{ for } k \leq i \leq \text{NROOT}.$$

The quantities

$$KK'(i,2) = \frac{1}{\beta_k'^2} \frac{1}{B'}\bigg|_{s = -\beta_k'} \qquad (\beta_k' = W3)$$

$$KK'(i,1) = \frac{1}{\beta_k'^2} \frac{D(s)}{B'(s)}\bigg|_{s = -\beta_k'}$$

$$KK'(i,3) = \frac{1}{\beta_k'^2} \frac{A(s)}{B'(s)}\bigg|_{s = -\beta_k'}$$

are calculated and stored in the array KK in one-to-one correspondence with the list $\{\beta_i'\}$ = ROOT(i).

The program repeats the entire process for the new interval (β_k', β_{k+1}').

The iteration continues until no roots can be found in the interval $(0,\beta_1)$, which means all the roots are stored in the array ROOT(i) in ascending order, and the array KK(i,j) contains the three quantities defined above, evaluated at each of the roots.

Step 5

Equation (II.19) is used to calculate X_{ri}, Y_{ri}, and Z_{ri}.

$$X_{ri} = i\Delta\left[\frac{D(s)}{B(s)}\right]\Bigg|_{s=0} + \frac{d}{ds}\left[\frac{D(s)}{B(s)}\right]\Bigg|_{s=0} + \sum_{k=1}^{NROOT} \frac{1}{\beta_k^2}\ \frac{D(s)}{B'(s)}\Bigg|_{s=-\beta_k} e^{-\beta_k \Delta i}$$

and similarly for Y_{ri} with D(s) replaced by 1, and Z_{ri} replaced by A(s).

Step 6

X_i, Y_i, and Z_i are obtained from X_{ri}, Y_{ri}, and Z_{ri} using Eq. (II.16).

Step 7

The series $\{X_i\}$, $\{Y_i\}$, and $\{Z_i\}$ are truncated.

If X_n, Y_n, and $Z_n \le 10^{-7}$, all terms $i \ge n$ are ignored. If

$$\left| \frac{X_{n-1}}{X_{n-2}} - \frac{X_n}{X_{n-1}} \right| <= 10^{-5}$$

and the same for Y_n and Z_n, terms with $i \ge n$ are ignored.

Step 8

Additional truncation is done to make sure terms are not kept once the series reaches the common ratio. The common ratio is

$$CR = e^{-\beta_1 \Delta}$$

where β_1 is the smallest root.

First, a check is made to make sure Y_i is past its maximum, and X_i and Z_i are past their minima, i.e., that Y_i is decreasing and X_i and Z_i are increasing. Second, a check is made to make sure the slope of Y_i is decreasing, and the slopes of X_i and Z_i are increasing. If these criteria are met, the final test is made for nearness to the common ratio:

$$\text{if} \quad \frac{\left|\frac{X_n}{X_{n-1}}\right| - CR}{CR} \le .005$$

and the same holds for Y_n and Z_n, then terms $i > n$ are not saved.

1.3 Description of the Subroutines

RESFAC

RESFAC is the main subroutine for calculating response factors. Its operation is described in the previous section. The X, Y, and Z response factors are stored in the arrays RFX(I), RFY(I), and RFZ(I). A maximum of 100 response factors can be calculated and stored. If the common ratio has not been reached in 100 terms, an error message is issued.

ZERO (RR, BETA, RES, M, K0, K1, M1, M4)

Subroutine ZERO calculates the quantities

$$K0 = U = \frac{1}{\sum_{i=1}^{NL} R_i} ,$$

$$K1 = \left[\frac{1}{B^2} \frac{dB}{ds} \right] \Bigg|_{s=0} ,$$

$$M1 = \frac{d}{ds} (A) \Bigg|_{s=0} , \text{ and}$$

$$M4 = \frac{d}{ds} (D) \Bigg|_{s=0} ,$$

using Eqs. (II.22), (II.26), and (II.27).

The Input Parameters

RR(i) resistance of ith layer

BETA(i) $d_i/\sqrt{\alpha_i}$

RES(i) RES(i) is always equal to zero and is effectively not used in DOE-2. There is a code in ZERO (and in all the other subroutines) to allow RES(i) to be a resistance parallel to RR(i). It would be the air gap resistance in a stud wall, and RR(i) would be the stud resistance.

M number of layers

The Output Parameters

Defined above.

FALSE (R, BETA, RES, W1, W2, W3, B1, B2, BP3, M, N)

Subroutine FALSE finds a root of B(s) in the interval s = (-W1, -W2).

FALSE first divides (W1, W2) into 20 subintervals. Starting at the lowest subinterval, it ascertains whether a root is in the subinterval by seeing if the sign of B is different at the lower and upper ends of the subinterval.

If a root is in the subinterval (a,b), (a,b) is bisected

$$c = a + \frac{b}{2}.$$

FALSE then finds if the root is in (a,c) or (b,c). If the sign of B at a is not equal to the sign of B at c, the root is in (a,c). Otherwise, it is in (c,b). The bisecting process continues until the size of the interval containing the root is $\leq 10^{-12}$.

If FALSE cannot find a root in the original subintervals, it decreases the size of the subintervals to (W2 - W1)/20·N and tries again. If this doesn't work, N is incremented by 1, new subintervals are defined as above, and FALSE tries again. The incrementing of N continues until FALSE successfully finds a root or until N > 25, in which case FALSE quits with no error message.

Input Parameters

R(i)	resistance of ith layer
BETA(i)	$d_i/\sqrt{\alpha_i}$
RES(i)	0 and is unused in DOE-2
W1	lower limit of the interval to be searched for a root of B
W2	upper limit of the interval to be searched for the root of B
M	number of layers
N	defined in text

Output Parameters

W3	position of root
B1	$D(s)\big\|_{s = -W3}$
B2	$A(s)\big\|_{s = -W3}$
BP3	$B'(s)\big\|_{s = -W3}$

FALSE calls DER and MATRIX.

SLOPE (R, BETA, RES, W1, W2, M, ICONT, LAST)

Subroutine SLOPE answers the question of whether there is a root of B in the interval (W1, W2).

If there is no root, ICONT is set to 2, and LAST (the present index of the interval to be searched) is decremented by 1.

If there is a root, ICONT is set to 1 and W2 is reset to define a smaller interval (W1, W2) in which a root exists.

The subroutine works by defining 20 new intervals:

$$(W1,\ W1 + \delta),\ (W1,\ W1 + 2\delta),\ \ldots\ ,$$

where $\delta = (W2 - W1)/20$.

The intervals are examined in succession. A root exists in the interval $(W1,\ W1 + i\delta)$ if B has a different sign at W1 than it has at $W1 + i\delta$, or if the derivative of B has changed sign twice in the interval. W2 is then reset to $W1 + i\delta$ when the routine returns.

Input Parameters

R(i) resistance of layer i

BETA(i) $d_i/\sqrt{\alpha_i}$

RES(i) 0 and is unused in DOE-2

W1 lower limit of search interval

W2 upper limit of search interval. Reset to upper limit of interval in which the root is known to exist.

M number of layers

LAST index of the interval being searched. The interval being searched is

$$(W1,\ W2) = (\beta_{LAST-1} + 10^{-5}/\Delta,\ \beta_{LAST} - 10^{-5}/\Delta)$$

where Δ = 1 hour in DOE-2. LAST is decremented by 1 if there is no root in (W1, W2).

Output Parameters

ICONT a flag; ICONT = 1 means there is a root in (W1, W2); ICONT = 2 means there is no root in (W1, W2).

SLOPE calls the subroutine DER.

MATRIX (RR, BETA, RES, W, M, F)

MATRIX calculates

$$[M]\Big|_{s=-W} = \begin{bmatrix} A & B \\ C & D \end{bmatrix}\Big|_{s=-W}$$

using Eqs. (II.21) and (II.24).

Input Parameters

RR(i) resistance of ith layer

BETA(i) $d_i/\sqrt{\alpha_i}$

RES(i) 0 and is unused in DOE-2

W $s = -W$ is where [M] is evaluated

M number of layers

Output Parameters

F $[M]\big|_{s=-W}$

DER (RR, BETA, RES, W, M, F, FF)

DER calculates

$$[M]\Big|_{s=-W} = \begin{bmatrix} A(s) & B(s) \\ C(s) & D(s) \end{bmatrix}\Big|_{s=-W}$$

and

$$\frac{d}{ds}[M]\Big|_{s=-W}$$

using Eqs. (II.21), (II.22), (II.24), and (II.28).

Input Parameters

RR(i) resistance of ith layer

BETA(i) $d_i/\sqrt{\alpha_i}$

RES(i) 0 and is unused in DOE-2

W s = -W is where [M] and d[M]/ds are evaluated

M number of layers

<u>Output Parameters</u>

$$F = \frac{d}{ds} [M]_{s = -W}$$

$$FF = [M]_{s = -W}$$

F and FF are 2 x 2 matrices.

2. WEIGHTING FACTORS

by J. F. Kerrisk

Note: This discussion of weighting factors is presented here in BDL because the calculation of weighting factors is actually part of BDL. The results of these calculations are, however, used later in LOADS and SYSTEMS.

2.1 Overview

2.1.1 Introduction

The DOE-2 computer program employs weighting factors for the calculation of thermal loads and room air temperatures (Ref. 2). The weighting-factor technique, first introduced by Mitalas and Stephenson (Refs. 3 and 4), is one of many methods that has been used or proposed for building energy analysis. It represents a compromise between simpler methods, such as a steady-state calculation that ignores the ability of the building mass to store energy, and more complex methods, such as complete energy-balance calculations. With the weighting-factor method, an hourly thermal-load calculation is performed based on a physical description of the building and that hour's ambient weather conditions (temperature, solar radiation, wind velocity, etc.). These loads are used, along with the characteristics and availability of heating or cooling systems for the building, to calculate air temperatures and heat extraction or heat addition rates. The weighting-factor technique provides a simple, flexible, fast, and efficient calculation method, which accounts for the important parameters that affect building energy analysis.

When working with HVAC problems, the user can normally seek out reference material, other than this manual, on most any subject. However, when working with weighting factors, there are few, if any, other sources that the user may refer to; that is why the following weighting factors discussion is so lengthy.

2.1.2 The DOE-2 Method of Calculation

The information of primary interest to a building designer is the heat-extraction (heat-addition) rate and air temperature of a room for a given set of conditions. DOE-2 provides these data by a two-step process.

First step. In the first step, which is performed in the LOADS program, the air temperature is assumed to be fixed at some reference value. Instantaneous heat gains (or losses) for the room are calculated on the basis of this constant temperature. Various types of heat gains, such as solar radiation entering through windows, energy from lights, people, or equipment, and conduction of energy through the walls, are considered. A cooling load for the room, which is defined as the rate at which energy must be removed from the room to maintain its air temperature fixed at the reference value, is calculated for each type of instantaneous heat gain. (To avoid dual discussions, one for cooling and one for heating, simply remember that heating loads and heat losses are merely negative cooling loads and heat gains.) The cooling load associated with a particular heating source can differ from the instantaneous heat gain for that same heating source. As an example, when solar radiation enters through the windows, some of the radiation may be absorbed (by the floor, walls, or furniture) and stored for later release to the air, thus reducing the current hour's cooling load. Weighting factors, one set for each type of heat gain considered, are used to calculate cooling loads from the instantaneous heat gains. These heat-gain weighting factors are merely a set of parameters that quantitatively determine how much of the energy that enters the room is stored and how fast that stored energy is released during later hours. The type of heat gain (e.g., solar energy entering through windows as compared to conduction through the walls) can affect the relative amounts of energy stored. For this reason, the weighting factors for each type of heat gain are different. Similarly, the construction of a room can influence how much incoming energy is stored and how rapidly it is released. Thus, different rooms can have different weighting factors.

At the end of the first step, the cooling loads from the various heat gains are summed to provide a total cooling load for the room.

Second step. In the second step of the process, which is performed in the SYSTEMS program, the total cooling load for a room, along with data about the HVAC system attached to the room and a set of air-temperature weighting factors, is used to calculate the actual heat-extraction rate and air temperature. The actual heat-extraction rate differs from the cooling load because, in practice, the air temperature varies from the reference value specified by the user in LOADS or because of HVAC system characteristics. The air-temperature weighting factors are a set of parameters that relate the net cooling load (the cooling load as determined by the LOADS simulator less any heat extraction, or addition, done by the HVAC system) to the deviation of the air temperature from the reference value specified in LOADS.

There are two general assumptions made with all weighting factors used in DOE-2. The first is that the process modeled can be represented by linear differential equations. This assumption is necessary because heat gains from various sources are calculated independently and are later summed to obtain the overall result (that is, the superposition principle is used). Therefore, nonlinear processes such as natural convection and radiation must be approximated linearly. The second general assumption is that system properties that influence the weighting factors are constant (that is, they are not functions of time or temperature). This requires that system properties, such as film coefficients and the distribution of incident radiation on surfaces, be represented by average values over the time of interest. Both assumptions represent limitations to the use of weighting factors. The linearity assumption (the first assumption) does not represent a really significant limitation, at this time, because the processes involved, even radiation, can be linearly approximated with sufficient accuracy for most calculations. The assumption of constant system properties (the second assumption) can limit the use of weighting factors in situations where important room properties actually do vary during a calculation. Two examples of this are (1) the distribution of solar radiation incident on the interior walls of a room, which can vary hourly, and (2) film coefficients, which can vary with direction of heat flow or air velocity.

2.1.3 Precalculated Weighting Factors

Precalculated weighting factors are weighting factors that have been calculated (and stored) for typical building rooms. These weighting factors can be selected for use in DOE-2. The data are based on the original ASHRAE weighting factors for rooms of light, medium, and heavy construction (Refs. 5 and 6). The mass of the room has been quantified by introduction of the FLOOR-WEIGHT parameter (Ref. 2), which represents the mass of building material associated with the room per unit floor area. The light, medium, and heavy constructions are characterized respectively by 30, 70, and 130 lb/ft^2 of floor area. If the FLOOR-WEIGHT of a room is specified by the user as exactly 30, 70, or 130 lb/ft^2, the ASHRAE weighting factors for that construction are used by DOE-2. As an extension of the ASHRAE precalculated weighting factors, a method has been added to DOE-2 that interpolates and extrapolates the precalculated weighting factors, as a function of FLOOR-WEIGHT. For values of the FLOOR-WEIGHT other than 30, 70, or 130 lb/ft^2, this method is employed to select the precalculated weighting factors. The method is more fully described in Sec. II.2.3.5.

There are many assumptions inherent in the precalculated weighting factors. When the user selects precalculated weighting factors, he is accepting not only the general assumption of linearity and constant system properties, but he is also accepting the entire construction of the typical rooms for the weighting-factor calculation. This includes items such as the construction and thermal properties of the walls, window area and orientation, amount and description of furniture, distribution of incoming solar radiation, radiative properties (for example, absorptivity) of the walls, interior film coefficients, and long-wavelength radiant exchange. For this reason, the precalculated weighting factors can only approximate the description of any building room.

2.1.4 Custom Weighting Factors

Custom weighting factors are a set of heat-gain and air-temperature weighting factors that are calculated by DOE-2 for a particular room, using an actual description of the room for the calculation. The user may employ custom weighting factors for any, or all, rooms in a building, specifying precalculated weighting factors for the remaining rooms. Room data that affect the custom weighting-factor calculation should represent averages for the entire RUN-PERIOD (see Chap. II. BDL). When custom weighting factors are requested, heat-gain weighting factors are calculated for (1) solar radiation into the room, (2) lighting within the room, (3) people or equipment within the room, and (4) conduction of energy into the room. Air-temperature weighting factors are also calculated. These custom weighting factors include the influence of room furniture, which is specified by the user.

The custom weighting factors represent a significant improvement over the precalculated weighting factors in a number of areas. The most significant improvement comes from the use of actual data, which describes the room, to calculate the weighting factors. As stated previously, the limitations of precalculated weighting factors are hard to quantify, so specific boundaries between the range of applicability of precalculated and custom weighting factors cannot be given. However, testing has indicated that custom weighting factors should be used for direct gain, passive solar buildings or other buildings with heavy construction and for buildings where solar energy provides a large part of the load.

2.2 Some Mathematical Preliminaries

2.2.1 Introduction

The introduction and use of the weighting-factor method for building energy analysis has been influenced by a number of constraints. The first constraint is that the differential equations, which describe heat flow in a building, are too complex for an analytical solution. Thus, some approximate method must be sought. A second constraint is that weather data (solar radiation, ambient temperature, etc.) that affect building performance are generally available only at "discrete" points in time, usually occurring at hourly intervals. Although interpolation techniques could provide continuous approximations to these discrete data,* a method such as the custom weighting-factor technique (which incorporates the discrete nature of the data and a scheme for interpolating between data points) simplifies the analysis. Another constraint is the inadequate availability of computer time and computer size. An efficient calculation technique is needed, especially for year-long analyses of large commercial buildings. Popular numerical methods, such as finite difference or finite element calculations, have been used for small buildings, usually for short time periods; they have proven to be too inefficient, however, for general use.

In summary, an ideal technique would be an efficient, approximate technique that incorporates the discrete nature of the data that drive the system. Weighting factors represent an application of z-transform methods (to be defined later) to the solution of differential equations (Refs. 7 and 8). The z-transform method has been widely used for the solution of discrete systems (difference equations). It represents the counterpart of Laplace transforms as applied to continuous systems (differential equations). In building energy analysis, the z-transform method represents an approximate solution to the differential equations that describe heat transfer in the building. An interpolation technique for the discrete input data is contained within the method. This method provides a common formalism for wall heat transfer (response-factor calculation) and for overall heat transfer within each room (weighting-factor calculations).

Section 2.2.2 relates some of the mathematical techniques required for an understanding of the weighting-factor method used in DOE-2. It is not a rigorous presentation, but functions mostly by example. A simple, ordinary differential equation is solved by a number of different techniques, including z-transform methods. This section provides some insight into the relationships between z-transform techniques and more conventional methods.

2.2.2 Solution of Differential Equations

Heat transfer in buildings can be simulated by differential equations. Transient heat transfer requires the solution of partial differential equations. In this section, a variety of techniques for solving the transient

* Discrete data, in this context, means data that are available only at discrete points in time, normally every hour (there are no data available between these points in time).

portion of heat-transfer equations is discussed. They range from analytic solutions to z-transform methods. As an aid in understanding the relationship between the various techniques, a simple, ordinary differential equation is solved in various ways. An ordinary differential equation is employed rather than a partial differential equation because it greatly simplifies the analysis, while still presenting the important concepts.

2.2.2.1 Conventional Solution of Differential Equations

In a few simple situations, analytic solutions to the differential equations that describe heat transfer are possible. However, in most instances, some approximate solution is required. In this section, a simple differential equation is used to give examples of (1) an analytic solution and (2) an approximate solution obtained by relatively conventional methods.

The differential equation

$$\frac{dy}{dt} + y = g(t), \tag{II.35}$$

is a linear, first order, ordinary differential equation for y as a function of t. The forcing function [g(t)] is indicated as a function of t. The solution can be written as

$$y = e^{-t} \int e^{t}\, g(t)dt + ce^{-t}, \tag{II.36}$$

where c is a constant evaluated from the initial conditions (Ref. 9). As a specific problem, let

$$\begin{aligned} g(t) &= 0 \quad \text{for } t < 0, \\ &= \sin \pi t \quad \text{for } 0 \le t \le 1, \\ &= 0 \quad \text{for } t > 1, \end{aligned} \tag{II.37}$$

and let $y = 0$ for $t \le 0$. The solution for y is then

$$y(t) = \frac{1}{1 + \pi^2} \left(\sin \pi t - \pi \cos \pi t + \pi e^{-t}\right) \quad \text{for } 0 \le t \le 1, \tag{II.38a}$$

and

$$y(t) = \frac{\pi}{1 + \pi^2} (e + 1)e^{-t} \quad \text{for } t > 1. \tag{II.38b}$$

Figure II.5 shows a plot of g(t) and y(t) as a function of t. The function y(t) increases as g(t) increases, lagging somewhat behind; y(t) decreases exponentially after g(t) becomes zero.

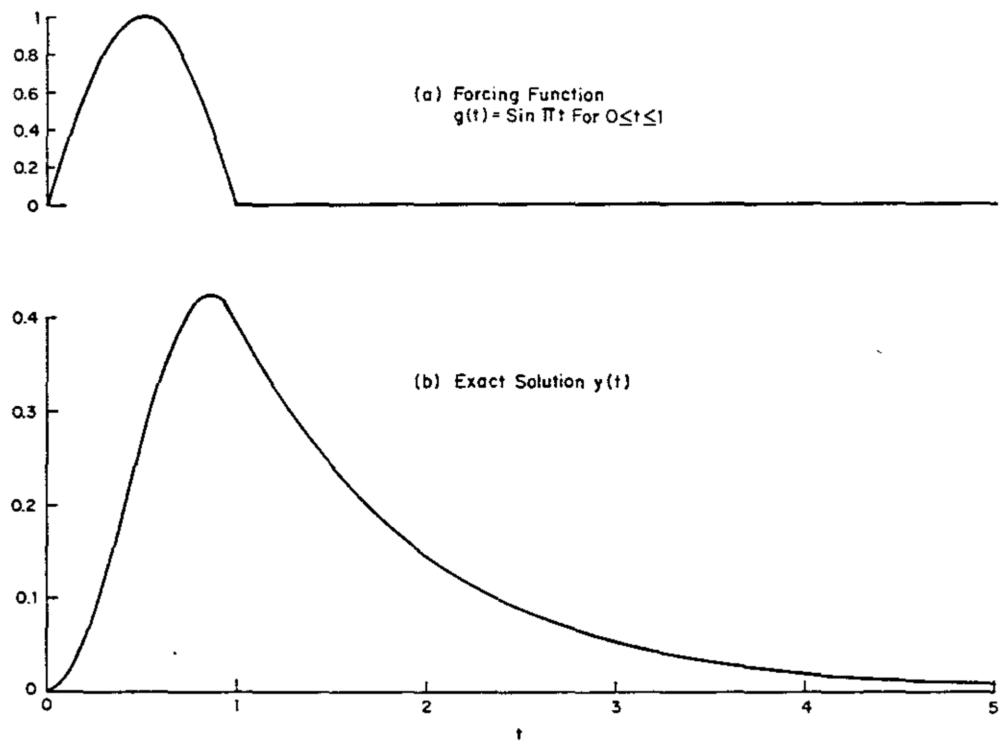


Fig. II.5. Forcing function and exact solution to Eq. (II.35).

As a prelude to an approximate solution to Eq. (II.35), consider the analytic solution for

$$\begin{aligned} g(t) &= 0 \quad \text{for } t < 0 \\ &= 1 \quad \text{for } 0 \leq t \leq \Delta \\ &= 0 \quad \text{for } t > \Delta. \end{aligned} \tag{II.39}$$

In this case, g(t) represents a square pulse of unit height and width Δ, starting at $t = 0$. Again, $y = 0$ for $t \le 0$. Using Eq. (II.36), the solution is

$$y = 1 - e^{-t} \quad \text{for } 0 \le t \le \Delta, \tag{II.40a}$$

and

$$y = (e^{\Delta} - 1)e^{-t} \quad \text{for } t > \Delta. \tag{II.40b}$$

The same method can be applied to a pulse starting at some general value of $t = t_0$. In this case, the solution would be

$$y = 0 \quad \text{for } t \le t_0, \tag{II.41a}$$

$$y = 1 - \exp(t_0 - t) \quad \text{for } t_0 \le t \le t_0 + \Delta, \tag{II.41b)*}$$

and

$$y = (e^{\Delta} - 1)\exp(t_0 - t) \quad \text{for } t > t_0 + \Delta. \tag{II.41c}$$

Any complex forcing function for Eq. (II.35) can be approximated by a sequence of square pulses. Since Eq. (II.35) is linear, the solution for that complex forcing function can be written as the sum of the solutions for the sequence of square pulses that approximate it. For an approximation of this type, the solution is usually calculated at a sequence of points, $t = t_0$, $t_0 + \Delta$, $t_0 + 2\Delta$, etc. As an example, for a unit pulse starting at $t = 0.4$ (i.e., $t_0 = 0.4$) with $\Delta = 0.1$, the solution to Eq. (II.35) at subsequent intervals of Δ can be obtained from Eqs. (II.41),

$$y(0.4) = Y_0 = 0$$

$$y(0.4 + 0.1) = Y_1 = (e^{0.1} - 1)\exp(0.4 - 0.5) = 0.09516,$$

$$y(0.4 + 0.2) = Y_2 = (e^{0.1} - 1)\exp(0.4 - 0.6) = 0.08611,$$

$$y(0.4 + 0.3) = Y_3 = (e^{0.1} - 1)\exp(0.4 - 0.7) = 0.07791, \text{ etc.}$$

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*Alternatively expressed as $y = 1 - e^{t_0 - t}$ for $t_0 \le t \le t_0 + \Delta$. Throughout the balance of this section, either method of showing e raised to a power will be used.

Figure II.6 shows a plot of the unit pulse and the solution, where the points have been connected by straight lines. Notice that only Eq. (II.41c) has been used for the approximation, simplifying the work considerably. For a unit pulse at some other time, the same sequence of values shown above would be involved, only shifted depending on the value of t_0.

Figure II.6 also shows g(t) given by Eq. (II.37), approximated by square pulses with $\Delta = 0.1$. The approximation is relatively crude, but it serves to illustrate the method. The first pulse (at $t_0 = 0$) has zero height, so it does not contribute to the solution. The second pulse (at $t_0 = 0.1$) has height $g(\Delta) = \sin(\pi\Delta) = 0.3090$. At subsequent times ($2\Delta$, 3Δ, etc.), it contributes

$$y_2(t = 0.2) = g(\Delta)(e^{0.1} - 1) \exp(0.1 - 0.2) = 0.02941,$$

$$y_2(t = 0.3) = g(\Delta)(e^{0.1} - 1) \exp(0.1 - 0.3) = 0.02661, \text{ etc.}$$

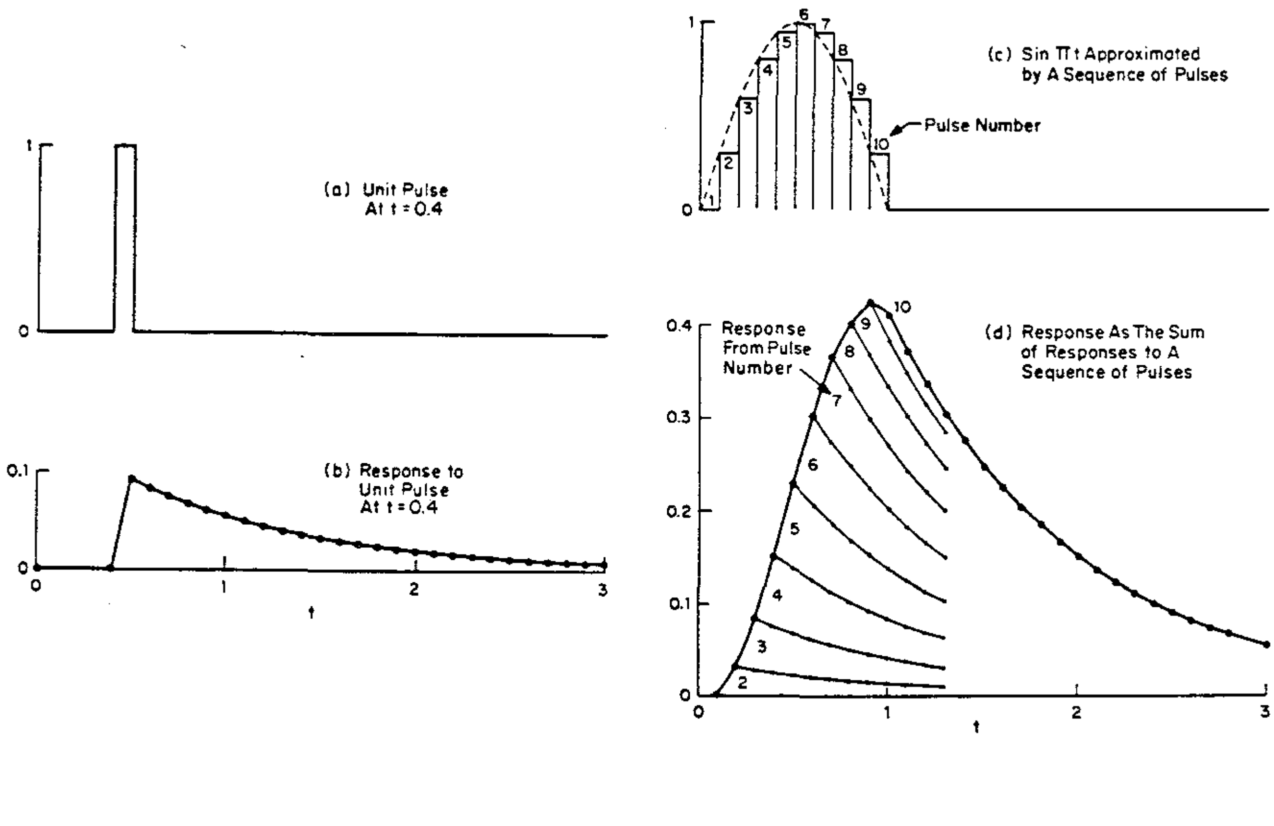

Fig. II.6. Plot of unit pulse and solution to Eq. (II.35).

The third pulse (at $t_0 = 0.2$) has height $g(2\Delta) = \sin(2\Delta\pi) = 0.5878$. At subsequent times ($3\Delta$, 4Δ, etc.), it contributes

$$y_3(t = 0.3) = g(2\Delta)(e^{0.1} - 1)\exp(0.2 - 0.3) = 0.05593$$

$$y_3(t = 0.4) = g(2\Delta)(e^{0.1} - 1)\exp(0.2 - 0.4) = 0.05061, \text{ etc.}$$

Thus, the solution at $t = n\Delta$ can be written as

$$y(t = n\Delta) = \sum_{j=1}^{n} y_j \ (t = n\Delta).$$

This can be rewritten as

$$y(n\Delta) = \sum_{j=1}^{n} Y_j \ g[(n-j)\Delta], \tag{II.42}$$

where $g(j\Delta) = \sin(j\Delta\pi)$, and

$$Y_j = (e^{\Delta} - 1)\exp(-j\Delta).$$

The solution, calculated in this manner, is also shown in Fig. II.6. An indication is given graphically in this figure of how the responses of the various pulses contribute to the total solution. A comparison of Figs. II.5 and II.6 shows that the approximate solution is quite good, considering the crude manner in which the forcing function was approximated.

2.2.2.2 Laplace Transform Methods

Although transform techniques would usually not be needed to solve Eq. (II.35), a discussion of Laplace transforms is useful as an introduction to z-transforms and the transfer-function methods that are the basis of weighting factors. The Laplace transform of a function f(t) is defined as (Refs. 10 and 11)

$$\bar{f}(s) = \int_0^{\infty} e^{-st} f(t)dt. \tag{II.43}$$

When applied to an ordinary differential equation for y(t), an algebraic equation in $\bar{y}(s)$ results. When applied to a one-dimensional, partial differential equation, an ordinary differential equation in the space variable results.

Thus, the Laplace transform replaces the derivative of a time variable with a simpler variation in terms of a complex frequency variable, s.

Taking Laplace transforms of both sides of Eq. (II.35) gives

$$s\bar{y}(s) - y(0) + \bar{y}(s) = \bar{g}(s),$$

or since we have been using $y(t) = 0$ at $t = 0$,

$$\bar{y}(s) = \frac{\bar{g}(s)}{1 + s} . \tag{II.44}$$

For a given $g(t)$, $\bar{g}(s)$ can be obtained from tables or from Eq. (II.43). Then $y(t)$ can be determined, also from tables or using the inversion theorem for Laplace transforms (Ref. 10). It can be verified (after some manipulation) that for $g(t)$ given by Eq. (II.37), the solution to Eq. (II.35) is given by Eq. (II.38).

The utility of Laplace transforms is not in their use for obtaining analytic solutions of the differential equations of building heat transfer, but rather in the formalism that allows a simple relation such as Eq. (II.44) to be written between the transforms of the forcing function [$g(t)$] and the response [$y(t)$] of a system. For an ordinary, linear differential equation, with zero initial conditions, the Laplace transforms of the input or forcing function and the output or response are in general related as

$$\frac{\bar{y}(s)}{\bar{g}(s)} = K(s), \tag{II.45}$$

where $K(s)$ is called the transfer function (Ref. 11). In addition, if the differential equation has constant coefficients, the transfer function will be an algebraic function having the form of the ratio of two polynomials in s. For the partial differential equations that describe building heat transfer Laplace transforms of the input and response can also be related as in Eq. (II.45) (Ref. 10). (The inputs and responses in building heat transfer generally involve temperatures and heat fluxes at specific locations.) The transfer function, however, is generally not algebraic in s, thus complicating the analysis considerably.

Assuming a transfer-function type relationship, the transfer function can be found as the response of the system to an input whose Laplace transform is unity (Ref. 11). The delta function or unit impulse, $\delta(t)$, is such a function (Ref. 12). If we define $y_i(t)$ as the response to a delta function and $\bar{y}_i(s)$ as the Laplace transform, then

$$\bar{y}_i(s) = \bar{\delta}(s)\, K(s) = K(s). \tag{II.46}$$

This technique is often employed to determine K(s). If $y_i(t)$ is known, another approach may be used to find the response to any other forcing function g(t) in terms of the convolution integral (Ref. 11),

$$y(t) = \int_0^t g(\tau)\, y_i(t - \tau)d\tau + y(0). \tag{II.47}$$

This relation, which is usually proved with the aid of Laplace transforms, will be referred to later.

If we return to the Laplace-transform solution to Eq. (II.35), the transfer function can be written by examination of Eq. (II.44) as

$$K(s) = \frac{1}{1 + s} .$$

This is the ratio of two polynomials in s, as noted above. Since this transfer function is also the Laplace transform of the response of Eq. (II.35) to a delta function, i.e., $K(s) = \overline{y}_i(s)$, $y_i(t)$ can be found in Laplace transform tables as the inverse of K(s), i.e.,

$$y_i(t) = e^{-t}.$$

For g(t) defined by Eq. (II.37), we can write the solution to Eq. (II.35) using the convolution integral as

$$y(t) = e^{-t}\int_0^t \sin\pi\tau\, e^{\tau} d\tau \qquad \text{for } 0 \le t \le 1,$$

and

$$y(t) = e^{-t}\int_0^1 \sin\pi\tau\, e^{\tau} d\tau \qquad \text{for } t > 1.$$

When evaluated, these integrals yield the same result obtained for the original analytic solution [Eq. (II.38)]. A strong resemblance can be seen between Eq. (II.47) and Eq. (II.42) that was obtained as an approximate solution to Eq. (II.35). In fact, they are analogous in that Eq. (II.42) was derived by summing the responses to a sequence of pulses of width Δ, while Eq. (II.47) was obtained by integrating the response from a delta function. Equation (II.47) is the continuous version and Eq. (II.42) is the discrete version of the same general relation.

2.2.2.3 z-Transform Methods

Laplace transforms are used with continuous functions, but there is an analogous transform, the z-tranform, that is used with discrete data (Refs. 7 and 8). If a continuous function f(t) is sampled at intervals of Δ, the result can be written in terms of the delta function as

$$f^*(t) = \sum_{i=0}^{\infty} f(i\Delta)\ \delta(t - i\Delta), \tag{II.48}$$

where the superscript * is used to indicate the discrete function. Figure II.7 shows an example for f(t) defined by Eq. (II.37) and $\Delta = 0.1$. The unique properties of the delta function allow a compact mathematical description, in the form of Eq. (II.48), of a discrete function. The Laplace transform of Eq. (II.48) is

$$\bar{f}^*(s) = \sum_{i=0}^{\infty} \int_0^{\infty} f(i\Delta)\ \delta(t - i\Delta)\ e^{-st}\ dt,$$

$$\bar{f}^*(s) = \sum_{i=0}^{\infty} f(i\Delta)\ e^{-i\Delta s}. \tag{II.49}$$

If the variable z is introduced as $z = e^{\Delta s}$, then Eq. (II.49) can be written as

$$\bar{f}^*(s) = f(z) = \sum_{i=0}^{\infty} f(i\Delta)\ z^{-n}, \tag{II.50}$$

where the notation f(z) is used to indicate the z-transform of f(t). Equation (II.50) represents a polynomial in z^{-1}, where the coefficients are values of the function f(t) at $t = \Delta, 2\Delta, 3\Delta$, etc. The utility of this formulation comes about when it is recognized that since a z-transform can be obtained from a Laplace transform by a variable change, the transfer-function concept applies equally well for z-transforms. Thus, z-transforms of the input and output can be related as

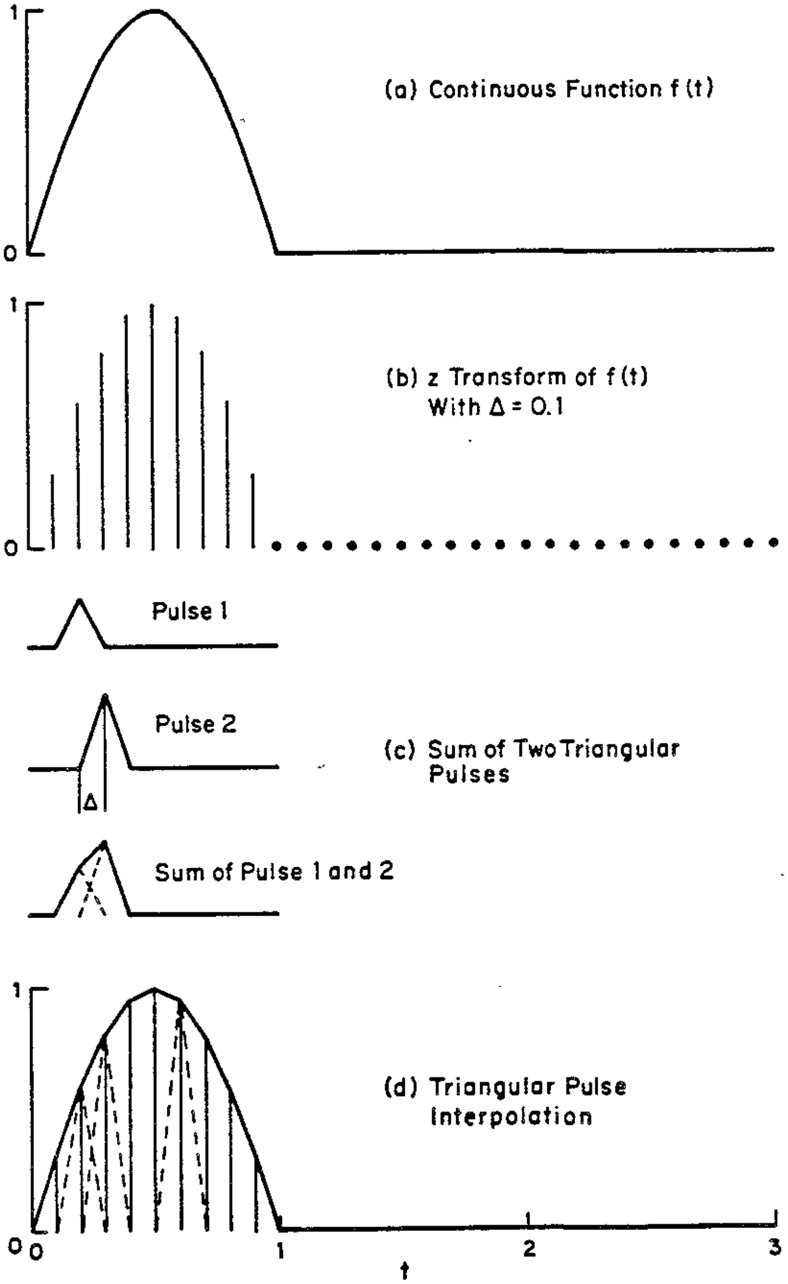

Fig. II.7. Example for f(t) defined by Eq. (II.37) and $\Delta = 0.1$.

$$\frac{y(z)}{g(z)} = K(z), \tag{II.51}$$

where y(z) and g(z) are the z-transforms of y(t) and g(t), respectively, and K(z) is the z-transfer function equivalent to the Laplace transfer function of the system. The restriction to linear differential equations with constant coefficients also holds here; however, extension of z-transform methods to nonlinear equations and to equations with variable coefficients is possible (Ref. 7). In most situations of practical interest, the z-transfer function can be expressed or expanded as the ratio of two polynomials in z^{-1}. This is true for the z-transfer functions employed in building energy analysis. Thus, we can write

$$K(z) = \frac{a_0 + a_1 z^{-1} + a_2 z^{-2} + \ldots}{b_0 + b_1 z^{-1} + b_2 z^{-2} + \ldots} , \tag{II.52}$$

where the a_i and b_i are constant coefficients. The simplicity of calculations using this formalism can be seen by writing the components of Eq. (II.51) in terms of their polynomial representations

$$\frac{y(0) + y(\Delta) z^{-1} + y(2\Delta) z^{-2} + \ldots}{g(0) + g(\Delta) z^{-1} + g(2\Delta) z^{-2} + \ldots} = \frac{a_0 + a_1 z^{-1} + a_2 z^{-2} + \ldots}{b_0 + b_1 z^{-1} + b_2 z^{-2} + \ldots} ,$$

where $y(0)$, $g(0)$, $y(\Delta)$, etc. are $y(t)$ and $g(t)$ evaluated at $t = 0$, Δ, 2Δ, etc. Because both sides of this equation are polynomials, the coefficients of the various powers of z^{-1} must be equal. This leads to

$$y(0) = \frac{1}{b_0} [a_0 \, g(0)],$$

$$y(\Delta) = \frac{1}{b_0} [a_0 \, g(\Delta) + a_1 \, g(0) - b_1 \, y(0)],$$

or for a general term

$$y(n\Delta) = \frac{1}{b_0} \Big(a_0 \, g(n\Delta) + a_1 \, g[(n-1)\Delta] + a_2 \, g[(n-2)\Delta] + \ldots$$

$$- b_1 \, y[(n-1)\Delta] - b_2 \, y[(n-2)\Delta] - \ldots \Big) .$$

The general term can be expressed more compactly as

$$b_0 \, y(n\Delta) = \sum_{j=0}^{n} a_j \, g[(n-j)\Delta] - \sum_{j=1}^{n} b_j \, y[(n-j)\Delta]. \tag{II.53}$$

The similarity of part of this equation to Eq. (II.42), the approximate solution obtained for Eq. (II.35) by conventional means, is immediately evident. Equation (II.53) relates the solution or output at any time $t = n\Delta$ to the input at $t = n\Delta$, along with the previous inputs and outputs of the system.

The final step required for the use of z-transforms is a method of determining the z-transfer function. The same technique used with Laplace transforms can be applied here, i.e., if we employ a forcing function or input whose z-transform is unity in a system with zero initial conditions, the z-transform of the response of the system will be the z-transfer function [see Eq. (II.46)]. With Laplace transforms, there was one such function, the delta function. With z-transforms, there are many (generally pulse shaped) functions whose z-transform is unity (Ref. 7). One such function is the unit-height, square pulse of width Δ that was used for the approximate solution of Eq. (II.35) in Sec. 2.2.2.1. The use of this pulse function is equivalent to interpolating the input by a sequence of square pulses (see Fig. II.6). As an example of the procedure followed, Eq. (II.35) will be solved in this manner. The starting point is the Laplace transformed version of Eq. (II.35),

$$\bar{y}(s) = y(z) = \frac{\bar{g}(s)}{1 + s}.$$

For g(t), a square pulse [see Eq. (II.39)], the Laplace transform of g(t) is (Ref. 7)

$$\bar{g}(s) = \frac{1}{s}\left(1 - e^{-\Delta s}\right) = \frac{1}{s}\left(1 - z^{-1}\right).$$

Thus, we have

$$y(z) = \frac{1 - z^{-1}}{s(1 + s)} . \tag{II.54}$$

Both Jury (Ref. 7), and Mitalas and Stephenson (Ref. 13) have listed tables of z-transforms equivalent to Laplace transforms; however, the Laplace transforms are generally of the form s^{-n} or $(s + \alpha)^{-n}$. Equation (II.54) can be put into this form by rewriting it as

$$y(z) = \left(1 - z^{-1}\right)\left(\frac{c}{s} + \frac{d}{1 + s}\right),$$

where c = 1 and d = -1. Replacing the terms in s by the equivalent z-transforms (Ref. 7) gives

$$y(z) = \left(1 - z^{-1}\right)\left(\frac{1}{1 - z^{-1}} - \frac{1}{1 - z^{-1}\, e^{-\Delta}}\right),$$

or rearranging terms

$$K(z) = y(z) = \frac{z^{-1}\,(1 - e^{-\Delta})}{1 - z^{-1}\, e^{-\Delta}}\,. \tag{II.55}$$

In terms of the general form of the z-transfer function, noted above, we have $a_1 = (1 - e^{-\Delta})$, $b_0 = 1$, $b_1 = -e^{-\Delta}$, and all other a_i and b_i equal to zero. The solution can thus be written as

$$y(n\Delta) = a_1\, g[(n-1)\Delta] - b_1\, y[(n-1)\Delta], \text{ or}$$

$$y(n\Delta) = (1 - e^{-\Delta})\, g[(n-1)\Delta] + e^{-\Delta}\, y[(n-1)\Delta]. \tag{II.56}$$

It is not immediately clear that Eq. (II.56) is equivalent to the previous solution to this problem, obtained by conventional means, Eq. (II.42). Here we have the output expressed as a function of one input and the previous output, while Eq. (II.42) expresses the output as a sum of previous inputs only. However, the Y_j in Eq. (II.42) is of a special form, in that

$$\frac{Y_2}{Y_1} = \frac{Y_3}{Y_2} = \frac{Y_{j+1}}{Y_j} = e^{-\Delta}, \tag{II.57}$$

where $e^{-\Delta}$ is the common ratio of the Y_i. Writing out the expressions for $y(n\Delta)$ and $y[(n-1)\Delta]$ from Eq. (II.42) gives

$$y(n\Delta) = Y_1\, g[(n-1)\Delta] + Y_2\, g[(n-2)\Delta] + Y_3\, g[(n-3)\Delta] + \ldots,$$

$$y[(n-1)\Delta] = Y_1\, g[(n-2)\Delta] + Y_2\, g[(n-3)\Delta] + Y_3\, g[(n-4)\Delta] + \ldots \quad .$$

Multiplying $y[(n-1)\Delta]$ by $e^{-\Delta}$ and subtracting from $y(n\Delta)$ produces

$$y(n\Delta) - e^{-\Delta}\, y[(n-1)\Delta] = Y_1\, g[(n-1)\Delta] + (Y_2 - e^{-\Delta} Y_1)\, g[(n-2)\Delta]$$

$$+ (Y_3 - e^{-\Delta} Y_2)\, g[(n-3)\Delta] + \ldots\,,$$

where by virtue of Eq. (II.57), all terms containing factors of the form $(Y_{j+1} - e^{-\Delta}Y_j)$ are zero. The result, with $Y_1 = (1 - e^{-\Delta})$, is identical to Eq. (II.56). This technique, of reformulating a z-transfer function from a single polynomial in z^{-1} to a ratio of polynomials, was developed by Lokmanhekim (Ref. 14). The constant ratio of terms is called the common ratio.

The last example in this section will be used to show how the accuracy of the z-transfer-function solution to Eq. (II.35) can be improved by employing a triangular pulse instead of the square pulse. Figure II.7 shows how two triangular pulses, offset by Δ, produce a piecewise-linear curve when summed. Also shown is a piecewise linear approximation to the forcing function defined by Eq. (II.37). A comparison between this approximation and that from the square pulse (see Fig. II.6) shows that the triangular pulse provides a much better approximation to the forcing function. Employing the same procedure that was used for the z-transform solution for a square pulse, we have

$$K(z) = \frac{\bar{g}(s)}{1 + s} .$$

For g(t), a triangular pulse, $\bar{g}(s)$ is given by (Ref. 7)

$$\bar{g}(s) = \frac{z(1 - z^{-1})^2}{\Delta s^2} ,$$

and

$$K(z) = \frac{z(1 - z^{-1})^2}{\Delta s^2 (1 + s)} = \frac{z(1 - z^{-1})^2}{\Delta} \left[\frac{c}{s^2} + \frac{d}{s} + \frac{e}{s + 1} \right] ,$$

with c = 1, d = -1, and e = 1. Substituting the equivalent z-transforms gives

$$K(z) = \frac{z(1 - z^{-1})^2}{\Delta} \left[\frac{\Delta}{z(1 - z^{-1})^2} - \frac{1}{(1 - z^{-1})} + \frac{1}{1 - z^{-1} - e^{-\Delta}} \right] .$$

Rearranging this into the form of Eq. (II.52) results in

$$K(z) = \frac{a_0 + a_1 z^{-1}}{b_0 + b_1 z^{-1}} , \qquad \text{(II.58)}$$

with

$$a_0 = 1 - \frac{1}{\Delta}(1 - e^{-\Delta}),$$

$$a_1 = -e^{-\Delta} + \frac{1}{\Delta}(1 - e^{-\Delta}),$$

$$b_0 = 1, \text{ and}$$

$$b_1 = -e^{-\Delta},$$

with all other a_i and b_i equal to zero. The equation for $y(n\Delta)$ can be written as

$$y(n\Delta) = \left[1 - \frac{1}{\Delta}(1 - e^{-\Delta})\right] g(n\Delta) + \left[-e^{-\Delta} + \frac{1}{\Delta}(1 - e^{-\Delta})\right] g[(n-1)\Delta]$$

$$+ e^{-\Delta} y[(n-1)\Delta]. \qquad \text{(II.59)}$$

Table II.2 lists values of $y(t)$ calculated at selected times for the exact solution [Eq. (II.38)], the square pulse z-transform solution [Eq. (II.56)], and the triangular pulse z-transform solution. It is evident that the triangular pulse provides a much better approximation for very little extra computation.

The z-transfer formalism for solving differential equations presented here is basically the technique used by Mitalas and Stephenson to describe heat transfer through multilayered walls (Ref. 13). For building energy analysis, only temperatures and heat fluxes at the inside and outside surfaces of a wall are required. The Laplace transformed differential equation for these quantities can be put in the form of Eq. (II.45) (Ref. 10). The process of finding the equivalent z-transform is, however, considerably more complex than that described for Eq. (II.35), requiring the numerical determination of roots of a nonlinear equation (Ref. 13). The resulting z-transfer function parameters, a_i and b_i, are the wall response factors, one set for each of the three unique heat-transfer processes occurring. As used in DOE-2, the response factors are calculated such that all $b_i = 0$ for $i \geq 2$. A somewhat different formalism, presented by Kusuda, gives equivalent results (Ref. 15).

TABLE II.2

COMPARISON OF VARIOUS SOLUTIONS TO EQ. (II.35)

t	Exact Solution	z-Transform Solution: Square Pulse	z-Transform Solution: Triangular Pulse
0	0	0	0
0.1	0.0151	0	0.0149
0.2	0.0569	0.0294	0.0564
0.3	0.1187	0.0825	0.1177
0.4	0.1919	0.1516	0.1903
0.5	0.2673	0.2277	0.2651
0.6	0.3354	0.3012	0.3327
0.7	0.3878	0.3631	0.3846
0.8	0.4178	0.4055	0.4143
0.9	0.4208	0.4229	0.4174
1.0	0.3954	0.4120	0.3921
2.0	0.1454	0.1516	0.1442
4.0	0.0197	0.0251	0.0195
6.0	0.0027	0.0028	0.0026

2.2.2.4 Lumped Parameter Representations

In dealing with heat transfer in walls, a partial differential equation was required to describe the temperature as a function of time and location in the wall. In many situations, it is only necessary to know the value of a variable at a few discrete spatial locations; for example, only temperatures and heat fluxes at the inside and outside surfaces of a wall are of practical value for most building energy analyses. If the overall behavior of a component, such as a wall or a quantity of furniture, can be characterized such that the response or variation in one parameter is known for a change in another parameter, that component can be represented by a single element with no spatial variation. By doing this, a problem involving partial differential equations can be reduced to one with only ordinary differential equations in the variable time. In terms of the previous discussions, if the transfer function of a component is known, the component can be treated as a "black box" in a system, simplifying the overall analysis of the system considerably. Finite difference heat-transfer calculations make use of this concept to describe the spatial variation of temperature and heat flux with a number of connected thermal resistances and capacitances. The properties of specific volumes of space are lumped into a few parameters. Once the transfer functions or response factors of a wall are known, the wall can be considered as a single component in further analyses. This concept greatly simplifies the analysis of the thermal behavior of entire rooms.

As an example of the analysis of a lumped parameter network, Fig. II.8a represents a simple resistance-capacitance circuit. Using the standard relations between the Laplace transforms of the current and voltage (Ref. 16),

$$\overline{i_R}(s)\ R = \overline{v}(s),$$

$$\frac{\overline{i_e}(s)}{sC} = \overline{v}(s),$$

and

$$\overline{i}(s) = \overline{i_R}(s) + \overline{i_c}(s) = (\frac{1}{R} + sC)\ \overline{v}(s).$$

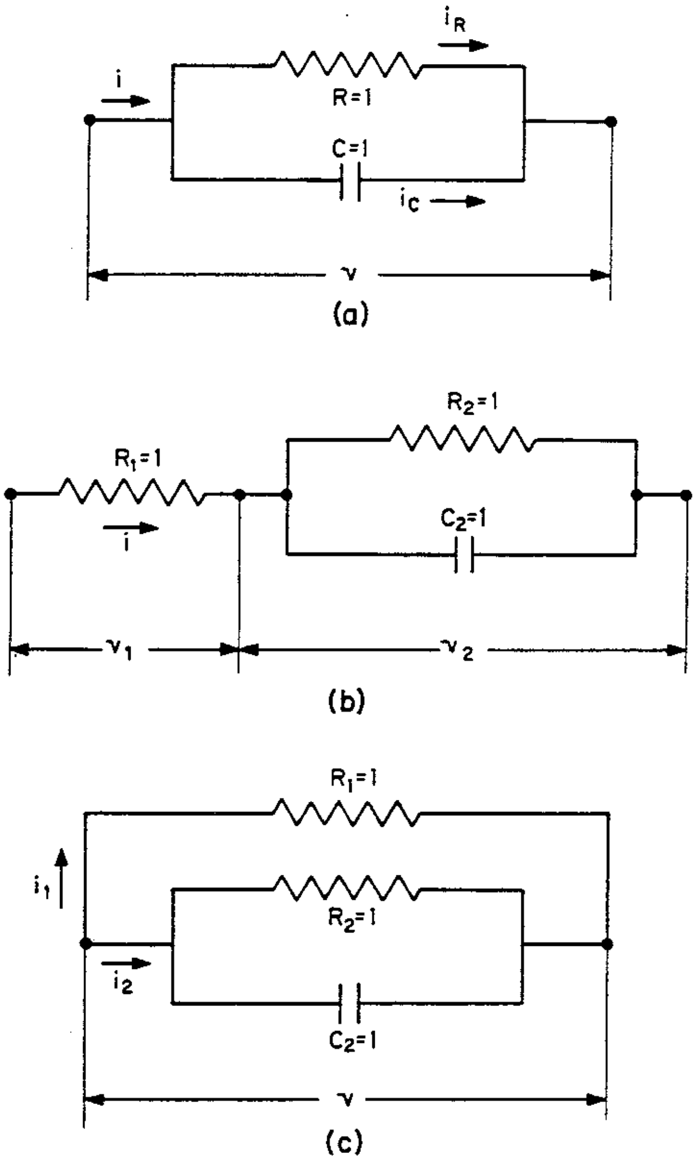

Fig. II.8. Resistance-capacitance circuit models.

For R = 1 and C = 1, this reduces to

$$\frac{\bar{v}(s)}{\bar{i}(s)} = \frac{1}{1 + s} ,$$

which is the Laplace transformed version of Eq. (II.35) with $\bar{v}(s) = \bar{y}(s)$ and $\bar{i}(s) = \bar{g}(s)$ [see Eq. (II.44)]. Thus, the circuit in Fig. II.8a is a graphical representation of Eq. (II.35). The Laplace transfer function and z-transfer functions obtained previously for this equation apply to the circuit.

Weighting factors involve heat transfer in an entire room. The important components in the room such as the walls, furniture, and room air must be interconnected to account for the convective and radiative heat flow that occurs. The physical basis for this procedure is discussed in Sec. 2.3; however, here it will be noted that the networks obtained are, in general, complex enough so that the solution technique discussed previously (obtaining the Laplace transfer function and converting it to the z-transfer function) is no longer practical. Rather, a method of directly combining the z-transfer functions for the various components of the room will be employed. The z-transfer functions for heat transfer in massive walls are already known in the form of their response factors, and the z-transfer functions for radiative and convective processes can easily be obtained (see Sec. 2.3). These z-transfer functions can be manipulated in the same manner as Laplace transfer functions; however, it should be recognized that the overall z-transfer function obtained from a combination of component z-transfer functions is, in general, only an approximation to the true overall z-transfer function (Ref. 8). The correct method requires that the Laplace transfer functions be combined and the z-transfer function equivalent to the overall Laplace transfer function be obtained. Since this method is impractical for entire rooms, the approximation is employed. To show how different results can be obtained by the two techniques, two examples will be given. The examples will use very simple circuits so that both techniques, the direct combination of z-transfer functions and the combination of Laplace transfer functions followed by finding the equivalent z-transfer function, can be employed. In the first example, the two methods give identical results; in the second example, different results are obtained.

The first example involves the series combination of a pure resistance with the parallel resistance-capacitance circuit shown previously (see Fig. II.8b). Two equations can be written for $v_1(z)$ and $v_2(z)$, which are the z-transforms of the voltage drops $v_1(t)$ and $v_2(t)$,

$$\frac{v_1(z)}{i(z)} = K_1(z) ,$$

and

$$\frac{v_2(z)}{i(z)} = K_2(z).$$

From the previous work, $K_2(z)$ is given by Eq. (II.58). Using the same technique, $K_1(z)$ can be written as

$$K_1(z) = R_1 = 1. \tag{II.60}$$

The transfer function for the overall voltage drop can be determined from

$$v(z) = v_1(z) + v_2(z) = [K_1(z) + K_2(z)]\ i(z) = K(z)\ i(z).$$

Thus,

$$K(z) = 1 + \frac{[1 - \frac{1}{\Delta}(1 - e^{-\Delta})] + [-e^{-\Delta} + \frac{1}{\Delta}(1 - e^{-\Delta})]\ z^{-1}}{1 - e^{-\Delta}\ z^{-1}} ,$$

or

$$K(z) = \frac{[2 - \frac{1}{\Delta}(1 - e^{-\Delta})] + [-2e^{-\Delta} + \frac{1}{\Delta}(1 - e^{-\Delta})]\ z^{-1}}{1 - e^{-\Delta}\ z^{-1}} . \tag{II.61}$$

In terms of Laplace transfer functions

$$\frac{\bar{v}_1(s)}{\bar{i}(s)} = K_1(s) = R_1 = 1,$$

and

$$\frac{\bar{v}_2(s)}{\bar{i}(s)} = K_2(s) = \frac{1}{1 + s} .$$

The resulting overall Laplace transfer function is

$$K(s) = K_1(s) + K_2(s) = \frac{2 + s}{1 + s} .$$

Using the techniques described in Sec. 2.2.2.2, the z-transfer function equivalent to this Laplace transfer function is identical to Eq. (II.61).

The second example involves the parallel combination of a pure resistance with the parallel resistance-capacitance circuit shown previously (see Fig. II.8c). Here, the two known z-transfer functions represent

$$\frac{v(z)}{i_1(z)} = K_1(z) = R_1 = 1,$$

and

$$\frac{v(z)}{i_2(z)} = K_2(z),$$

where $K_2(z)$ is again given by Eq. (II.58). To combine $K_1(z)$ and $K_2(z)$, we note that

$$i(z) = i_1(z) + i_2(z) = v(z)\ [K_1^{-1}(z) + K_2^{-1}(z)],$$

or

$$\frac{v(z)}{i(z)} = K(z) = \frac{K_1(z)\ K_2(z)}{K_1(z) + K_2(z)} .$$

In this case,

$$K(z) = \frac{\left[\dfrac{1 - \frac{1}{\Delta}(1 - e^{-\Delta})}{2 - \frac{1}{\Delta}(1 - e^{-\Delta})}\right] + \left[\dfrac{-e^{-\Delta} + \frac{1}{\Delta}(1 - e^{-\Delta})}{2 - \frac{1}{\Delta}(1 - e^{-\Delta})}\right] z^{-1}}{1 + \left[\dfrac{-2e^{-\Delta} + \frac{1}{\Delta}(1 - e^{-\Delta})}{2 - \frac{1}{\Delta}(1 - e^{-\Delta})}\right] z^{-1}} . \qquad \text{(II.62)}$$

In terms of Laplace transfer functions,

$$\frac{\bar{v}(s)}{\bar{i}_1(s)} = K_1(s) = R_1 = 1,$$

$$\frac{\bar{v}(s)}{\bar{i}_2(s)} = K_2(s) = \frac{1}{1 + s},$$

and

$$\frac{\bar{v}(s)}{\bar{i}_2(s)} = K_{(s)} = \frac{1}{2 + s}.$$

The z-transfer function equivalent to this Laplace transfer function is

$$K(z) = \frac{\left[\frac{1}{2} - \frac{1}{4\Delta}\left(1 - e^{-\Delta}\right)\right] + \left[-\frac{1}{2}e^{-2\Delta} + \frac{1}{4}\left(1 - e^{-2\Delta}\right)\right]z^{-1}}{1 - e^{-2\Delta}\,z^{-1}} . \qquad \text{(II.63)}$$

No amount of algebraic manipulation can force Eq. (II.62) to be equivalent to Eq. (II.63); however, the coefficients [a_0, a_1, and b_1 as defined in Eq. (II.52)] are very close. For $\Delta = 0.1$ in Eq. (II.62), the direct combination of z-transfer functions, $a_0 = 0.04614$, $a_1 = 0.04463$, and $b_1 = -0.81846$. For Eq. (II.63), the combination of Laplace transfer functions with subsequent conversion to z-transfer functions, $a_0 = 0.04683$, $a_1 = 0.04381$, and $b_1 = 0.81873$.

In these two examples, the z-transfer functions of the individual components were simple enough so that they could be algebraically manipulated. In problems involving real rooms, this is no longer true. For this reason, a time-step method is employed. In this method, a unit-pulse input is still used to find the transfer function of the network; the unit pulse is applied at the location in the network corresponding to the input. Individual outputs from each transfer function in the network are calculated at each time step. Some of these outputs may act as inputs to other transfer functions. The output for the process of interest is saved at each time step. This sequence of outputs represents a z-transfer function for that process in that network. The transfer function is in the form of Eq. (II.52) with $b_0 = 1$ and all other $b_i = 0$. There are various methods, one of which was described in Sec. 2.2.2.1, that a z-transfer function in this form can be converted into a ratio of two polynomials. As an example of this technique, the z-transfer function for the circuit in Fig. II.8b will be obtained. The two transfer functions that make up this circuit are given by Eqs. (II.58) and (II.60). For calculations, the individual voltage drops can be written as

$$v_1(n\Delta) = i(n\Delta),$$

and

$$v_2(n\Delta) = a_0\ i(n\Delta) + a_1\ i[(n-1)\Delta] - b_1\ v_2[(n-1)\Delta].$$

The unit-pulse current will be specified as

$$i(n\Delta) = 1 \quad \text{for } n = 0$$

$$= 0 \quad \text{for } n > 0.$$

For $\Delta = 0.1$, the values of a_0, a_1, and b_1 can be calculated from Eq. (II.59) as $a_0 = 0.04837$, $a_1 = 0.04679$, and $b_1 = -0.90484$. Table II.3 shows the resulting sequence of overall voltages $[v(n\Delta) = v_1(n\Delta) + v_2(n\Delta)]$ obtained in this manner. This sequence represents the transfer function for the circuit. If it is noted that for $n \geq 1$

$$\frac{v[(n+1)\Delta]}{v(n\Delta)} = 0.90484 = e^{-\Delta}.$$

TABLE II.3

SOLUTION FOR UNIT PULSE INPUT TO CIRCUIT IN FIG. II.8b

n*	$i(n\Delta)$	$v_1(n\Delta)$	$v_2(n\Delta)$	$v(n\Delta)$
0	1	1	0.04837	1.04837
1	0	0	0.09056	0.09056
2	0	0	0.08194	0.08194
3	0	0	0.07414	0.07414
4	0	0	0.06709	0.06709
5	0	0	0.06070	0.06070
.	.	.	.	.
.	.	.	.	.
.	.	.	.	.
.	.	.	.	.
n	0	0	$v_2(\Delta)\ e^{-(n-1)\Delta}$	$v(\Delta)\ e^{-(n-1)\Delta}$

* $t = n\Delta$ with $\Delta = 0.1$.

This infinite sequence can be changed from

$$K(z) = 1.04837 + 0.09056\ z^{-1} + 0.08194\ z^{-2} + \ldots$$

into

$$K(z) = \frac{1.04837 - 0.85805\ z^{-1}}{1 - 0.90484\ z^{-1}} \tag{II.64}$$

by the method discussed in Sec. 2.2.2.3. This is the same as Eq. (II.61) when the coefficients are evaluated for $\Delta = 0.1$.

The time-step method provides the same results that would be obtained from an algebraic manipulation of the individual z-transfer functions into one overall z-transfer function. The resulting overall z-transfer function is always in the form of an infinite sequence; additional operations are required to bring it into the form of the ratio of two polynomials. The use of the time-step method does not change the fact that working with a network of the individual z-transfer functions results in an approximate set of weighting factors. No assessment of the magnitude of the errors involved in this approximation has been made.

2.2.3 Conclusion

Section 2.2 has provided some insight into the mathematical techniques on which weighting factors are based. In particular, the z-transfer method for solving differential equations has been reviewed. As in much of mathematics, there are many paths that could be taken from a physical description of the problem of heat transfer in a room to a set of equations for the quantities desired. For example, the convolution integral [Eq. (II.47)] could have been approximated directly to give the same results as were obtained with z-transforms. The z-transform method was used here partly for historical reasons and partly because it provides a compact mathematical representation for handling the discrete data involved in building energy analysis.

The z-transform method represents a counterpart of Laplace transforms as applied to continuous systems. For this reason, much of the literature on z-transforms is in electrical engineering texts and journals (Refs. 7, 8, and 17). For a more rigorous treatment of z-transforms and their applications, Ref. 7 is a good starting point. It contains further references to much of the earlier work in this area.

2.3. Calculation of Weighting Factors

2.3.1. Introduction

The weighting factors used in DOE-2 represent z-transfer functions of the form described in Section II.2.2. There are two groups of weighting factors, the heat-gain weighting factors and the air-temperature weighting factors. The heat-gain weighting factors represent transfer functions that relate the space cooling load to the instantaneous space heat gains. Instantaneous heat gains from five different sources are considered: solar radiation entering through windows, general lighting, task lighting, energy from people and equipment, and energy entering by conduction through walls. The main differences between these heat sources are (1) the relative amounts of energy appearing as convection to the air versus radiation and (2) the distribution of the radiant energy, i.e., the relative intensities of radiation on different walls and furniture. Variations in these two characteristics result in different weighting factors for the five sources. Air-temperature weighting factors represent a transfer function that relates room air temperature to the net energy load of the room. All the weighting factors are z-transfer functions in the form of Eq. (II.52).

The weighting-factor calculation starts with a description of the various components that make up a room such as walls and furniture. The z-transfer functions for delayed walls are known in the form of their response factors. The Y and Z response factors of walls enter into the weighting-factor calculation. The z-transfer functions for quick surfaces are easily obtained from the thermal resistance or U-value of the surface. Also, response factors for typical kinds of furniture are available in DOE-2. These various components are connected to the room air by convection and are interconnected by radiation. The z-transfer functions for the convective and radiative energy transfer are also easily obtained from convective and radiative heat-transfer coefficients. The resulting description of the room can be thought of as a network in which various components that <u>can</u> store energy (delayed walls and furniture) and other components that <u>cannot</u> store energy (quick walls, windows, and room air) have specific temperatures and can interchange energy by convection and radiation.

The heat-gain weighting factors are all determined with the air temperature held fixed at its reference value, because the cooling load is defined as the energy that must be removed or added to the room air to hold its temperature fixed at the reference value. A detailed description of the calculation procedure is given in Sec. II.2.3.2; the procedure for solar weighting factors will be qualitatively discussed here as a preview of the method. Solar weighting factors represent a transfer function that relates the cooling load (output) to a flux of solar energy incident on the inside surfaces of a room (input). The transfer function is determined by using the time-step method with the network that describes the room. A pulse of energy is input to the inside surfaces of the walls for the first hour. The distribution of energy to the various walls is specified as input to DOE-2.

The total energy in the pulse is normalized to one so that pulse is a unit pulse. Some of the radiant energy incident on the walls is absorbed and stored, some is transferred to the air by convection, and some is transferred to other surfaces by radiation. The various transfer functions in the network determine the relative amounts of energy in these three modes. A time step of one hour is used since the wall response factors are calculated using this increment. At each time step (including $t = 0$), the energy flow to the room air represents the amount of the initial pulse that is a cooling load. Thus, an infinite sequence of cooling loads is generated, representing a z-transfer function in the form of Eq. (II.52) with $b_0 = 1$ and all other $b_i = 0$. Section II.2.3.3.1 describes how this sequence is converted into a set of weighting factors.

The other heat-gain weighting factors are determined in the same manner as the solar weighting factors. Different weighting factors result because some of the initial energy pulse from these sources goes directly to the air by convection during the first hour, and the distribution of radiant energy on the walls is usually different than for solar. For the air-temperature weighting factors, a unit pulse in room air temperature is applied for the first hour. The sequence of cooling loads determined in this manner specifies the air-temperature weighting factors.

Section II.2.3 describes the method used to determine custom weighting factors in DOE-2. The technique employed to obtain precalculated weighting factors has been described by Mitalas and Stephenson (Ref. 3 and 4). It is generally similar to the method used here, however, some differences do exist. Major differences between the two methods will be noted in the following sections as the DOE-2 method is described. The development in Sec. II.2.3.2.2 and II.2.3.2.3) is based on the work of Z. Cumali and his associates (Ref. 18).

2.3.2 Heat Balance Network for a Room

2.3.2.1 Network Components

The heat-balance network represents a model of heat transfer occurring inside a room. The network is constructed from a heat balance on the inside surface of all walls in the room. Four processes are considered: (1) conduction through the walls (and in furniture), (2) convection from inside surfaces to the room air, (3) radiation among the inside surfaces in the room, and (4) radiant sources impinging on the interior surfaces such as solar radiation or energy from lights. For any wall, energy reaching the inside surface by conduction can be written in terms of a transfer function as

$$Q_{Di}(z) = K_{Di}(z)\ T_i(z) - K'_{Di}(z)\ T'_i(z),$$

where $Q_{Di}(z)$ is the z-transform of the heat flow to the inside surface of wall i by conduction, $T_i(z)$ and $T'_i(z)$ are the z-transforms of the inside and outside surface temperatures of wall i (relative to some reference temperature) and $K_{Di}(z)$ and $K'_{Di}(z)$ are the z-transfer functions, which relate the conduction energy flow at the inside surface of wall i (output) to temperature changes of the inside and outside surfaces of the wall (input). For delayed walls, $K_{Di}(z)$ can be written in terms of the Z-response factors of the wall as

$$K_{Di}(z) = A_i \sum_{j=0}^{\infty} Z_i(j)\, z^{-j},$$

where the sequence $Z_i(0)$, $Z_i(1)$, $Z_i(2)$, ..., are the Z-response factors of wall i and A_i is the wall area. Similarly,

$$K'_{Di}(z) = A_i \sum_{j=0}^{\infty} Y_i(j)\, z^{-j},$$

where the sequence $Y_i(0)$, $Y_i(1)$, ..., are the Y-response factors for wall i. For a quick wall (with negligible thermal storage),

$$K_{Di}(z) = U_i A_i = \frac{1}{R_i},$$

where R_i is the thermal resistance of wall i. This relation follows from the analysis in Sec. II.2.2.2.4 and holds for any heat flow path with no thermal storage (pure resistance). Furniture can be treated in the same manner as a wall. The only difference is that furniture has no direct thermal connection to the exterior of the room, i.e., it behaves like a wall with heavy exterior insulation. Two sets of Z-response factors for furniture (light and heavy weight) are available in DOE-2. A detailed description of how furniture is modeled is given in Sec. II.2.3.4.1; in the following treatment, furniture will be considered as another wall.

Convective heat transfer between wall surfaces and room air can be written as

$$Q_{ci}(z) = K_{ci}(z)\,[T_a(z) - T_i(z)],$$

where $Q_{ci}(z)$ is the z-transform of the heat flow from the room air to the inside surface of wall i, $T_a(z)$ and $T_i(z)$ are the z-transforms of the air temperature and the surface temperature of wall i, and $K_{ci}(z)$ is the z-transfer function for the process. Since this process involves no energy storage (the heat capacity of the air is considered negligible compared to the walls and furniture),

$$K_{ci}(z) = h_{ci}\ A_i,$$

where h_{ci} is the convective heat transfer coefficient for wall i. This analysis considers convection as linear in the temperature difference with a constant coefficient. Neither of these assumptions is completely true. The linearity assumption is often made and can be justified as long as wall temperatures and air temperatures are relatively constant. However, h_c is known to vary significantly with direction of heat flow to horizontal surfaces (Ref. 19). Since the weighting factors may be applied where heat flow in any direction occurs, it is best to use an average value of h_c for the weighting-factor calculation.

Radiative heat transfer between two surfaces can be written as

$$Q_{Rim}(z) = K_{Rim}(z)\ [T_m(z) - T_i(z)],$$

where $Q_{Rim}(z)$ is the z-transform of the radiative heat flow from surface i to surface m, $T_i(z)$ and $T_m(z)$ are the z-transforms of the surface temperatures, and $K_{Rim}(z)$ is the z-transfer function for the process. In DOE-2, $K_{Rim}(z)$ is approximated as (Ref. 19)

$$K_{Rim}(z) = 4(\varepsilon_i)\sigma(T_R^3)(F_{im})(A_i) = G_{im}, \tag{II.65}$$

where ε_i is the emissivity of surface i, σ is the Stefan-Boltzmann constant, T_R is a reference temperature in absolute units, F_{im} is the view factor between surfaces i and m, and A_i of the area of the radiating surface. At present, all ε_i are assumed to be the same ($\varepsilon_i = 0.9$) and T_R is taken as 530°R (70°F), so that $4\varepsilon_i\sigma T_R^3$ is a constant (0.90) for all surfaces. The view factor is approximated as $F_{im} = A_m/A_T$, where A_m is the surface area receiving the radiant energy, and A_T is the total area of all surfaces in the room. If surface i cannot see surface m, such as two surfaces in the same plane like a window in a wall, F_{im} and F_{mi} are set to zero. As with convection, radiation is considered a linear process with a constant coefficient. Even though radiation is very nonlinear, an approximation such as Eq. (II.65) is often justified in practice, particularly if surface temperatures are restricted to a relatively narrow range as with heat flow in a room. The assumptions that T_R and ε_i are constants are not severe in this context. The approximation of F_{im} with area ratios is good for rooms that are close to cubes, but poor for elongated rooms.

Infiltration provides a direct heat flow path between the outside air and the room air. This can be written as

$$Q_V(z) = K_V(z)[T_a(z) - T_o(z)],$$

where $Q_V(z)$ is the z-transform of the heat flow from the room air to the exterior, $T_a(z)$ and $T_o(z)$ are the z-transforms of the room air temperature and the outside air temperature, and $K_V(z)$ is the z-transfer function for the process. Infiltration rates are usually estimated as a volumetric flow of exterior air into the room (V_{in}). For this case

$$K_V(z) = \rho_a \, C_{pa} \, V_{in},$$

where ρ_a and C_{pa} are the density and heat capacity of the exterior air.

There are numerous sources of radiant energy in a room such as solar energy or radiation from people or equipment. The z-transforms of these sources are known from hourly input values in the solar routines or from schedules, which have been specified for the sources in the room. These sources can be used directly in an energy balance. They will be designated as $Q_{si}(z)$ for the z-transform of the total source energy on the inside surface of wall i.

2.3.2.2 Heat Balance

An heat balance on the inside surface of wall i results in

$$Q_{Di}(z) = Q_{ci}(z) + \sum_{m=1}^{N} Q_{Rim}(z) + Q_{si}(z), \qquad (II.66)$$

where N is the number of surfaces in the room. Since the wall surface itself has no capacity for energy storage, the energy supplied by convection and radiation must equal the energy lost by conduction. Infiltration does not appear in the energy balance since it is a direct communication between the room air and the exterior. In terms of z-transfer functions, Eq. (II.66) can be rewritten as

$$K_{Di}(z)\, T_i(z) - K'_{Di}(z)\, T'_i(z) = K_{ci}(z)\, [T_a(z) - T_i(z)]$$

$$+ \sum_{m=1}^{N} K_{Rim}(z)\, [T_m(z) - T_i(z)] + Q_{si}(z). \qquad (II.67)$$

Each wall contributes one equation of this form. The equations are not independent owing to interwall radiation; thus, each equation involves surface temperatures for all walls. This system of equations represents the overall set of z-transfer functions that must be employed to obtain the weighting factors. As noted in Sec. II.2.2, the z-transfer function for a process can be determined as the output from a unit pulse input to a system with zero initial conditions. For the heat-gain weighting factors, a unit pulse in the radiant source terms $[Q_{si}(z)]$ is employed, while holding the air temperatures fixed (at zero for convenience).

For the air-temperature weighting factors, a unit pulse in the air temperature is used. The radiant source terms are held at zero for this calculation. When the room air temperature is pulsed, heat loss by infiltration must also be considered during the time the air temperature differs from zero. This loss represents a path that is independent of any walls in the room and can thus be determined independently. For both kinds of weighting factors, the wall surface temperatures are the unknowns or output desired. Using $T_i(z)$, along with $K_{ci}(z)$ and $T_a(z)$, the cooling load can be calculated.

2.3.2.3 Transfer Function

Although the z-transfer function, which relates $T_i(z)$ to source-term or air-temperatures pulse inputs, could, in principle, be determined by algebraic manipulation of the Eq. (II.67) set, the time-step method discussed in Sec. II.2.2.2.4 provides a more practical solution. To use this method, the polynomial representations of the z-transforms and z-transfer functions must be expanded to allow $T_i(k\Delta)$, $k = 0, 1, 2, \ldots$, which is the inside surface temperature of wall i at time $k\Delta$, to be isolated. To be compatible with the wall response factors, Δ is taken as one hour. At time $t = k\Delta$, this gives

$$A_i\, Z_i(0)\, T_i(k\Delta) + A_i \sum_{j=1}^{\infty} Z_i(j)\, T_i[(k-j)\Delta] = h_{ci}[T_a(k\Delta) - T_i(k\Delta)]$$

$$+ \sum_{m=1}^{N} G_{im}[T_m(k\Delta) - T_i(k\Delta)] + Q_{si}(k\Delta) + A_i \sum_{j=0}^{\infty} Y_i(j)\, T_i'[(k-j)\Delta],$$

or rearranging,

$$A_i\left[Z_i(0) + h_{ci} + \sum_{m=1}^{N} G_{im}\right] T_i(k\Delta) - A_i \sum_{m=1}^{N} G_{im}\, T_m(k\Delta) =$$

$$- A_i \sum_{j=1}^{\infty} Z_i(j)\, T_i[(k-j)\Delta] + h_{ci}\, T_a(k\Delta) + Q_{si}(k\Delta)$$

$$+ A_i \sum_{j=0}^{\infty} Y_i(j)\, T_i'[(k-j)\Delta]. \tag{II.68}$$

For this equation, the more familiar versions of the z-transfer functions have been substituted for $K_{Di}(z)$, $K_{ci}(z)$, and $K_{Rim}(z)$. The zero initial conditions are set by starting with all temperatures at zero. Since we are looking for transfer functions that relate the inside surface temperatures to source-temperature and air-temperature variations, the exterior surface temperatures of the walls ($T_i'[(k-j)\Delta]$ can be fixed (at zero) during the calculation. Thus, the term

$$A_i \sum_{j=0}^{\infty} Y_i(j)\, T_i'[(k-j)\Delta]$$

need not be considered further. The remaining terms in the Eq. (II.68) set can be written in matrix form as

$$\begin{bmatrix} C_{11} & C_{12} & \cdots & C_{1N} \\ C_{21} & C_{22} & \cdots & \\ \cdot & & & \\ \cdot & & & \\ \cdot & & & \\ \cdot & & & \\ C_{N1} & C_{N2} & \cdots & C_{NN} \end{bmatrix} \begin{bmatrix} T_1(k\Delta) \\ T_2(k\Delta) \\ \cdot \\ \cdot \\ \cdot \\ \cdot \\ T_N(k\Delta) \end{bmatrix} = \begin{bmatrix} A_1 h_{c1} T_a(k\Delta) + Q_{s1}(k\Delta) - \phi_1(k\Delta) \\ A_2 h_{c2} T_a(k\Delta) + Q_{s2}(k\Delta) - \phi_2(k\Delta) \\ \cdot \\ \cdot \\ \cdot \\ \cdot \\ A_N h_{cN} T_a(k\Delta) + Q_{sN}(k\Delta) - \phi_N(k\Delta) \end{bmatrix} \tag{II.69}$$

where

$$C_{ii} = A_i \left[Z_i(0) + h_{ci} + \sum_{m=1}^{N} G_{im} \right],$$

$$C_{im} = -A_i G_{im} = -A_m G_{mi},$$

and

$$\phi_i(k\Delta) = A_i \sum_{j=1}^{k} Z_i(j)\; T_i[(k-j)\Delta]. \tag{II.70}$$

If we define the terms on the right-hand side of Eq. (II.69) as $B_i(k\Delta)$, then

$$B_i(k\Delta) = A_i\, h_{ci}\, T_a(k\Delta) + Q_{si}(k\Delta) - \phi_i(k\Delta).$$

In matrix notation, Eq. (II.69) can be written as

$$\tilde{C}\,\tilde{T} = \tilde{B}, \tag{II.71}$$

where the notation $\tilde{C}$ indicates the matrix of terms c_{im}. The solution of Eq. (II.71) is

$$\tilde{T} = \tilde{C}^{-1}\,\tilde{B} = \tilde{D}\,\tilde{B}, \tag{II.72}$$

where $\tilde{D} = \tilde{C}^{-1}$ is the inverse of $\tilde{C}$. Since the elements of $\tilde{C}$ are constant, $\tilde{C}$ need only be inverted once for a given room. The formal solution of Eq. (II.71) can be written in terms of the individual surface temperatures as

$$T_i(k\Delta) = \sum_{m=1}^{N} D_{im}\, B_m(k\Delta). \tag{II.73}$$

The heat-gain weighting factors require calculation of $T_i(k\Delta)$ that results from a unit pulse in the radiant source terms. For this case

$$\sum_{i=1}^{N} Q_{si}(0) = 1,$$

$$Q_{si}(k\Delta) = 0 \qquad \text{for } k > 0, \text{ and}$$

$$T_a(k\Delta) = 0 \qquad \text{for } k \geq 0. \tag{II.74}$$

The relative distribution among the $Q_{si}(0)$ is provided by input to DOE-2. For the air-temperature weighting factors, a unit pulse in the air temperature is used. In this case,

$$T_a(0) = 1,$$

$$T_a(k\Delta) = 0 \quad \text{for } k > 0, \text{ and}$$

$$Q_{si}(k\Delta) = 0 \quad \text{for } k \geq 0. \tag{II.75}$$

The time-step calculation starts at zero time, i.e., k = 0. Since we start with zero temperatures,

$$B_i(0) = A_i\, h_{ci}\, T_a(0) + Q_{si}(0). \tag{II.76}$$

At time greater than zero, we have

$$B_i(k\Delta) = -\,\phi_i(k\Delta) \tag{II.77}$$

by virtue of Eqs. (II.74) and (II.75). Although $\phi_i(k\Delta)$ could be evaluated directly from Eq. (II.70), a rather compact recursion relation can be developed (Ref. 18). This relation eliminates much of the effort required to determine $\phi_i(k\Delta)$. The quantity $T_i[(k-j)\Delta]$ in Eq. (II.70) can be replaced with the formal solution given by Eq. (II.73), resulting in

$$\phi_i(k\Delta) = A_i \sum_{j=1}^{k} Z_i(j) \left\{ \sum_{m=1}^{N} D_{im}\, B_m[(k-j)\Delta] \right\}.$$

Making use of Eqs. (II.76) and (II.77), we can write

$$\phi_i(k\Delta) = A_i\, Z_i(k) \sum_{m=1}^{N} D_{im}\, B_m(0) - A_i \sum_{j=1}^{k-1} Z_i(j) \left\{ \sum_{m=1}^{N} D_{im}\, \phi_m[(k-j)\Delta] \right\}, \tag{II.78}$$

where the first term has separated the j = k term from the sum on j. The cooling load at time $k\Delta$ can be written as

$$Q(k\Delta) = \sum_{i=1}^{N} Q_i(k\Delta) = \sum_{i=1}^{N} A_i \; h_{ci}[T_a(k\Delta) - T_i(k\Delta)] + \frac{T_a(k\Delta)}{R_{inf}} , \tag{II.79}$$

where $Q_i(k\Delta)$ is the cooling-load contribution from wall i. The last term in this equation represents the contribution to the cooling load from infiltration; R_{inf} is the infiltration resistance, defined as

$$R_{inf} = \frac{1}{\rho_a \; C_{p_a} \; V_{in}} .$$

At time zero, we have

$$Q_i(0) = A_i \; h_{ci}\left[T_a(0) - \sum_{m=1}^{N} D_{im} \; B_m(0)\right] + \frac{T_a(0)}{R_{inf}} , \tag{II.80}$$

where $B_m(0)$ is given by Eq. (II.76). For $k > 0$, we can write

$$Q_i(k\Delta) = - A_i \; h_{ci} \; T_i(k\Delta) = A_i \; h_{ci} \sum_{m=1}^{N} D_{im} \; \phi_m(k\Delta). \tag{II.81}$$

Substituting for $\phi_m(k\Delta)$ from Eq. (II.78) results in

$$Q_i(k\Delta) = A_i \; h_{ci} \sum_{m=1}^{N} D_{im} \left[A_m \; Z_m(k) \sum_{n=1}^{N} D_{in} \; B_n(0)\right]$$

$$- A_i \; h_{ci} \sum_{m=1}^{N} D_{im} \left\{A_m \sum_{j=1}^{k-1} Z_m(j) \sum_{n=1}^{N} D_{mn} \; \phi_n[(k-j)\Delta]\right\},$$

or by use of Eq. (II.81),

$$Q_i(k\Delta) = A_i\ h_{ci} \sum_{m=1}^{N} D_{im} \left[A_m\ Z_m(k) \sum_{n=1}^{N} D_{mn}\ B_n(0) \right]$$

$$- A_i\ h_{ci} \sum_{m=1}^{N} D_{im} \left\{ \frac{1}{h_{cm}} \sum_{j=1}^{k-1} Z_m(j)\ Q_m[(k-j)\Delta] \right\} . \qquad \text{(II.82)}$$

Equation (II.82) expresses the cooling-load contribution from each wall at time $k\Delta$ in terms of past values of that variable. The total cooling loads, $Q(k\Delta)$, represent the coefficients in the z-transfer function for this process, i.e.,

$$T(z) = Q(0) + Q(\Delta)\ z^{-1} + Q(2\Delta)\ z^{-2} + \ldots .$$

At this point, we have an expression to generate a sequence of cooling loads $[Q(k\Delta),\ k = 0, 1, 2, \ldots]$ that results from a unit pulse in the radiant source or the air temperature. This sequence represents the z-transfer function, which relates the cooling load to that input. The transfer function can be used to determine the response of the room to any other input whose z-transform is known by use of Eq. (II.53). From a practical standpoint, the calculation of successive $Q(k\Delta)$ must stop at some value of k. In DOE-2, the calculation is continued until the common ratio

$$CR_k = \frac{Q(k\Delta)}{Q[(k-1)\Delta]}$$

becomes sufficiently constant. The current criterion stops the calculation sequence when

$$\left| \frac{CR_k - CR_{k-1}}{CR_{k-1}} \right| < 10^{-4}.$$

This technique completely defines the sequence in the same manner that a finite number of terms and a common ratio were used to define an infinite sequence in Sec. II.2.2.2.3.

The procedures of Sec. II.2.3.2.1 through II.2.3.2.3 have used response factors of delayed walls directly in the calculation. A similar weighting-factor calculation method has recently been developed in which delayed wall heat transfer is described by simple resistance-capacitance circuits (Ref. 20). Appropriate values of thermal resistance and capacitance for a wall can be calculated from the wall response factors. The general formulation of the problem in terms of z-transfer functions is the same as was presented here. The z-transfer functions of delayed walls are merely different. This method has the advantage of eliminating the requirement of a one-hour time step for the weighting-factor calculation. Its major disadvantage is that heat transfer in delayed walls is approximated by single-capacitor circuits. This approximation is acceptable for light walls, but becomes poorer as the mass of the wall increases. The recursion relation represented by Eq. (II.82) also proved to be a faster calculation method. For these reasons, the recursion relation was used as the basis for weighting-factor calculations in DOE-2.

The method employed by Mitalas and Stephenson to obtain precalculated weighting factors is very similar to that presented in Sec. II.2.3.2.1 through II.2.3.2.3) (Ref. 3 and 4). They did not obtain the recursion relationship [Eq. (II.82)]; however, they solved Eq. (II.71) using expressions for $\phi_i(k\Delta)$ as given by Eq. (II.70). They also determined the weighting factors for radiant source terms (such as solar weighting factors) differently. In DOE-2, a given source is distributed among all walls in a room and one calculation gives the weighting factors for that distribution. Mitalas and Stephenson calculated sets of weighting factors for a unit pulse on each wall in the room in a separate calculation. The resulting sets of weighting factors were then combined in proportion to the radiant distribution of sources to obtain the weighting factors for that distribution. Since we are dealing with linear systems, the two methods are equivalent.

2.3.3 Weighting Factors

2.3.3.1 Final Form of the Transfer Function

The z-transfer functions developed in Sec. II.2.3.2.3 could be used just as they were calculated, i.e., as a transfer function of the form

$$T(z) = d_0 + d_1 z^{-1} + d_2 z^{-2} + \dots , \qquad \text{(II.83)}$$

where $d_i = Q(i\Delta)$ is the cooling load calculated from the time-step method for the process. This form, however, would require storage for a large number of past values of the excitation function (input) and completion of a long sum at each hour of the simulation. For this reason, a more compact form of the transfer function will be sought. In particular, for the heat-gain weighting factors, a transfer function of the form

$$T(z) = \frac{\nu_0 + \nu_1 z^{-1} + \nu_2 z^{-2}}{1 + w_1 z^{-1} + w_2 z^{-2}} \qquad \text{(II.84)}$$

will be sought. The notation used is based on ASHRAE literature, where v_0, v_1, v_2, w_1, and w_2 are the weighting factors (Ref. 5 and 6). The transfer function sought for the air-temperature weighting factors will be

$$T(z) = \frac{g_0 + g_1 z^{-1} + g_2 z^{-2} + g_3 z^{-3}}{1 + p_1 z^{-1} + p_2 z^{-2}} . \qquad \text{(II.85)}$$

Again, the notation is from ASHRAE literature with the g_i and p_i being the weighting factors. The choices have been made partly for historical reasons. The precalculated weighting factors are in the form of Eqs. (II.84) and (II.85) except that v_2, w_2, g_3, and p_2 are zero (Ref. 5). Additional coefficients have been added in an attempt to better approximate the behavior of heavy rooms.

Two approaches have been used to convert a transfer function in the form of Eq. (II.83) into that of Eqs. (II.84) and (II.85). The first is a repeated application of the common ratio technique, discussed in Sec. II.2.2.2.3 (Ref. 14). As noted in Sec. II.2.3.2.3, the calculation of the cooling-load sequence $d_i = Q(i\Delta)$ was stopped when the common ratio of successive terms became sufficiently constant. Call this common ratio c_1. Using the technique described in Sec. II.2.2.2.3, Eq. (II.83) can be rewritten as

$$T(z) = \frac{d_0 + d_1' z^{-1} + d_2' z^{-2} + \ldots d_m z^{-m}}{1 - c_1 z^{-1}} , \qquad \text{(II.86)}$$

where $d_i' = d_i - c_1 d_{i-1}$ for $1 \le i \le m$, and m is the value of i such that

$$\frac{d_{i+1}}{d_i} = c_1$$

to sufficient accuracy for $i > m$. This same procedure can be applied to Eq. (II.86). Let c_2 be the common ratio found for the d_i' such that

$$\frac{d_{i+1}'}{d_i'} = c_2$$

to sufficient accuracy for $i > n$. Eq. (II.86) can then be rewritten as

$$T(z) = \frac{d_0 + d_1''z^{-1} + d_2''z^{-2} + \ldots d_n''z^{-n}}{1 - (c_1 + c_2)z^{-1} + (c_1c_2)z^{-2}}, \tag{II.87}$$

where $d_i'' = d_i' - c_2d_{i-1}'$ for $1 \le i \le n < m$. Equation (II.87) is close to the form of Eqs. (II.84) and (II.85) in that it has two terms in the denominator polynomial in z^{-1}. However, it would be fortuitous that the number of terms in the numerator polynomial was exactly what was needed, i.e., n was 2 or 3. This is a sign that Eqs. (II.84) and (II.85) can only approximate Eq. (II.83). One method (Ref. 20) of making the approximation, in the case of Eq. (II.84), is

$$\nu_0 = d_0,\ \nu_1 = d_1'',\ w_1 = -(c_1 + c_2),\ w_2 = c_1c_2, \text{ and } \nu_2 = \sum_{i=2}^{n} d_i''.$$

Repeated use of the common ratio method has been mentioned here for completeness. This technique is not employed in DOE-2.

The second approach to converting Eq. (II.83) into Eqs. (II.84) or (II.85), which is the one used in DOE-2, starts with a recognition that an approximation is involved and determines the weighting factors (ν_i and w_i or g_i and p_i) by solution of a set of simultaneous equations. Using the heat-gain weighting factors as an example, we can equate Eq. (II.83) to Eq. (II.84) since we want both equations to represent the same transfer function,

$$d_0 + d_1z^{-1} + d_2z^{-2} + \ldots = \frac{\nu_0 + \nu_1z^{-1} + \nu_2z^{-2}}{1 + w_1z^{-1} + w_2z^{-2}}.$$

Combining coefficients of like powers of z^{-1} (see Sec. II.2.2.2.3) leads to a set of equations of the form

$$\begin{aligned}
\nu_0 &= d_0,\\
\nu_1 &= d_1 + d_0w_1,\\
\nu_2 &= d_2 + d_1w_1 + d_0w_2,\\
0 &= d_3 + d_2w_1 + d_1w_2, \text{ etc.}
\end{aligned} \tag{II.88}$$

Five equations are required to determine the five weighting factors ν_0, ν_1, ν_2, w_1, and w_2. The first four are Eqs. (II.88). The last equation represents an energy balance. This aspect of the weighting factors is discussed more fully in Sec. II.2.3.3.2. Here, it will simply be noted that the last equation is

$$f = \sum_{i=0}^{\infty} d_i = \sum_{i=0}^{m} d_i + \frac{d_{m+1}}{1 - c_1} = \frac{\nu_0 + \nu_1 + \nu_2}{1 + w_1 + w_2} \; . \qquad \text{(II.89)}$$

For the air-temperature weighting factors, a sixth equation following the Eqs. (II.88) sequence is required. These five (or six) equations can easily be solved for the weighting factors by any number of linear algebra methods (Ref. 21). The only problem that has been encountered with this method occurs when the d_i coefficients decay rapidly to zero for increasing i (as might occur for a very light structure). In this case, the linear system becomes singular, or nearly singular, which is an indication that some of the weighting factors in Eq. (II.84) or (II.85) should be zero. DOE-2 will automatically request fewer weighting factors when near singularity occurs.

The two approaches to determining the weighting factors generate slightly different approximations to Eq. (II.83). Assuming k weighting factors are to be determined [k is 5 for Eq. (II.84) and 6 for Eq. (II.85)], the transfer function generated by the simultaneous-solution method will give the exact same results as Eq. (II.83) for the first k-1 time steps (hours) and will conserve energy as noted by Eq. (II.89). The transfer function generated by the common-ratio method will give the exact same results as Eq. (II.83) for the first k-2 time steps, will conserve energy, and will have the same common ratio as Eq. (II.83). In practice, both methods give reasonable approximations to Eq. (II.83). The simultaneous-solution technique was easier to implement for a general number of weighting factors and was chosen for DOE-2 on that basis. It has not been possible to ascertain from published information what approach was used to determine the precalculated weighting-factor values.

2.3.3.2 Application and Properties of Weighting Factors

Heat-gain weighting factors are used to determine cooling loads from various instantaneous heat gains, such as solar energy that enters a room or energy from lights or equipment. The instantaneous heat gains are known as a sequence of hourly values from solar routines or from schedules of equipment usage, lighting, etc. Given the heat gains q_0, q_1, q_2, ..., q_τ, ... as input, where the subscript indicates the hour of occurrence of the heat gain, and considering the cooling loads Q_0, Q_1, ..., as output, the formal z-transfer-function relation [equivalent to Eq. (II.81)] can be written as

$$\frac{Q(z)}{q(z)} = \frac{\nu_0 + \nu_1 z^{-1} + \nu_2 z^{-2}}{1 + w_1 z^{-1} + w_2 z^{-2}} \; , \qquad \text{(II.90)}$$

where q(z) and Q(z) are the z-transforms of the heat gain and cooling load, respectively. The equivalent of Eq. (II.53) then becomes

$$Q_\tau = v_0 q_\tau + v_1 q_{\tau-1} + v_2 q_{\tau-2} - w_1 Q_{\tau-1} - w_2 Q_{\tau-2}, \tag{II.91}$$

which is the way cooling loads are calculated in DOE-2. Thus, two past values of the heat gain and cooling load must be saved during the calculation. At the start of a calculation, past values of Q_τ and q_τ are not available. The usual starting assumption is that past values are zero. For this reason, DOE-2 repeats the first day's simulation three times as an initialization or startup procedure. This technique effectively assumes that the previous history of the building is identical to the conditions for the first day. The three-day startup period has proven adequate for all but very heavy structures.

The air-temperature weighting factors were determined as the cooling load that results from a unit pulse in air temperature. However, when they are used, the net cooling load (cooling load less any heat extraction or addition done by the HVAC system) is known and the air temperature (actually the deviation from the reference value set during the LOADS calculation) is determined. The equivalent to the formal z-transfer-function relation [Eq. (II.51)] is

$$\frac{Q(z)}{t(z)} = \frac{g_0 + g_1 z^{-1} + g_2 z^{-2} + g_3 z^{-3}}{1 + p_1 z^{-1} + p_2 z^{-2}}, \tag{II.92}$$

where Q(z) is the z-transform of the net cooling load and t(z) is the z-transform of the temperature deviation, i.e.,

$$t(z) = T(z) - T_R,$$

where T(z) is the z-transform of the air temperature and T_R is the reference temperature employed for the LOADS calculation. The equivalent to Eq. (II.53) is

$$Q_\tau = g_0 t_\tau + g_1 t_{\tau-1} + g_2 t_{\tau-2} + g_3 t_{\tau-3} - p_1 Q_{\tau-1} - p_2 Q_{\tau-2}. \tag{II.93}$$

However, we are interested in solving for t_τ, so that

$$t_\tau = \frac{1}{g_0} [Q_\tau + p_1 Q_{\tau-1} + p_2 Q_{\tau-2} - g_1 t_{\tau-1} - g_2 t_{\tau-2} - g_3 t_{\tau-3}]. \tag{II.94}$$

This is the basis of the air-temperature calculation in DOE-2. The three-day startup period is also used to minimize the effect of assuming past values of Q_T and t_T as zero initially.

Some interesting properties of the weighting factors can be obtained from consideration of Eqs. (II.91) and (II.93). The heat-gain weighting factors are all dimensionless because they are parameters in a transfer function between an input and output with the same units. Consider a room with a set of heat-gain weighting factors given by ν_0, ν_1, ν_2, w_1, and w_2. For a unit pulse heat gain q_0, q_1, q_2, ... with $q_0 = 1$ and all other $q_i = 0$, the cooling loads are

$$Q_0 = \nu_0$$

$$Q_1 = \nu_1 - w_1 Q_0$$

$$Q_2 = \nu_2 - w_2 Q_0 - w_1 Q_1$$

$$Q_3 = - w_2 Q_1 - w_1 Q_2, \text{ etc.} \tag{II.95}$$

The total cooling load can be written as

$$Q_T = \sum_{i=0}^{\infty} Q_i = \nu_0 + \nu_1 + \nu_2 - w_1 \sum_{i=0}^{\infty} Q_i - w_2 \sum_{i=0}^{\infty} Q_i,$$

or rearranging,

$$Q_T = \frac{\nu_0 + \nu_1 + \nu_2}{1 + w_1 + w_2} = f. \tag{II.96}$$

Because a unit pulse was used, f represents the fraction of the heat gain that appears as a cooling load. [See Sec. II.2.3.4.2 for a variation of Eq. (II.96) for solar weighting factors.] The fact that some of the energy is lost from the room is understandable in terms of conduction through the walls to the exterior. The quantity f is a characteristic of the room; it will be close to one for well-insulated rooms. Equation (II.96) was one of the relations used for the simultaneous-solution method of calculating weighting factors (see Sec. II.2.3.3.1). The same relation [Eq. (II.96)] can be obtained from a steady-state example. For a constant heat gain ($q_i = q$ for all i), the cooling load will also be constant (i.e., $Q_i = Q$ for all i). In this case, we have

$$\frac{Q}{q} = \frac{\nu_0 + \nu_1 + \nu_2}{1 + w_1 + w_2} = f,$$

and f represents the fraction of the steady state heat gain that appears as a cooling load.

The various coefficients making up the weighting factors exert their primary influence at different times. The cooling loads represented by Eq. (II.95), which result from a unit pulse in heat gain at hour zero, provide an example. At hour zero, the cooling load is ν_0. Thus, ν_0 represents the fraction of the heat gain that appears as a cooling load in that hour. In this respect, it is a strong function of the type of heat-gain source as well as the construction of the room. Similarly, $(\nu_1 - w_1 \nu_0)$ represents the fraction of the heat gain that appears as a cooling load in hour one. In general, ν_0, ν_1, and ν_2 will depend on the type of heat-gain source as well as on the construction of the room. As noted, when discussing common ratios in Sec. II.2.3.3.1, w_1 and w_2 are related to the cooling-load sequence at long times after the initial pulse. Thus, they are characteristic of how the room releases stored energy long after the initial pulse. For this reason, they tend to be nearly independent of the type of heat-gain source and a function only of the construction of the room. The parameters p_1 and p_2 for the air-temperature weighting factors will be similar to w_1 and w_2 for the same room. As an example of these relations, Table II.4 is a DOE-2 printed output page that lists the custom weighting factors generated during one such calculation. Custom weighting factors for four rooms, in a single-family residence, are listed.

The air-temperature weighting factors are coefficients in a transfer function between an input and output with different units. If the Q_i have units of Btu/hr and the t_i have units of °F, an examination of Eq. (II.94) indicates the p_i are dimensionless and the g_i have units of Btu/hr-°F. Under steady state conditions (all $Q_i = Q$ and all $t_i = t$), Eq. (II.94) can be rearranged to

$$\frac{Q}{t} = \frac{g_0 + g_1 + g_2 + g_3}{1 + p_1 + p_2} = K_T, \qquad \text{(II.97)}$$

where K_T is the conductance of the room that is inherent in the weighting factors. This conductance includes all heat flow paths such as infiltration, as well as conduction through the walls.

In ASHRAE literature, the precalculated air-temperature weighting factors are presented as normalized weighting factors (Ref. 5 and 6). The normalization procedure attempts to do two things (1) remove the effect of the room conductance and (2) remove the effect of room size. The effects of room conductance are separated by assuming that the cooling load can be separated into two parts, that part due to room conductance (Q_i') and the remainder (Q_i''), and that

TABLE II.4

SAMPLE DOE-2 CUSTOM WEIGHTING FACTOR OUTPUT

williamson house — at santa fe, new mexico
driven by special weather files — direct gain passive solar
custom weighting factor summary

	living wf1c	kitchen wf2c	garage wf4c	study wf3c
solar				
v0	.15880	.19571	.31567	.17643
v1	-.14015	-.16930	-.30170	-.16050
v2	.01050	.01212	.01842	.01237
w1	1.40172	1.35098	1.21027	1.40613
w2	-.43929	-.39778	-.27006	-.44223
general lighting				
v0	.46267	.50529	.51413	.45230
v1	-.59026	-.61243	-.56518	-.55282
v2	.16158	.15036	.09139	.13892
w1	1.41800	1.35768	1.21027	1.37613
w2	-.45768	-.40652	-.27006	-.42154
task lighting				
v0	.46267	.50529	.51413	.45230
v1	-.59026	-.61243	-.56518	-.55282
v2	.16158	.15036	.09139	.13892
w1	1.41800	1.35768	1.21027	1.37613
w2	-.45768	-.40652	-.27006	-.42154
people-equipment				
v0	.47024	.51225	.52097	.46001
v1	-.60192	-.62293	-.57427	-.56442
v2	.16575	.15396	.09391	.14290
w1	1.41800	1.35768	1.21027	1.37613
w2	-.45768	-.40652	-.27006	-.42154
conduction				
v0	.53705	.57431	.61695	.57405
v1	-.70483	-.71642	-.70170	-.73585
v2	.20256	.18610	.12920	.20174
w1	1.41800	1.35768	1.21027	1.37613
w2	-.45768	-.40652	-.27006	-.42154
air temp				
g0*	1.21427	1.26273	.93288	2.52293
g1*	-2.04922	-2.10975	-1.54277	-4.18281
g2*	.83951	.85414	.62144	1.67474
g3*	-.00456	-.00712	-.01155	-.01486
p1	-1.52318	-1.47709	-1.23898	-1.46421
p2	.54961	.50847	.28934	.49811

$$Q_i' = K_T\, t_i, \tag{II.98}$$

i.e., that Q_i' is proportional to the temperature deviation from the reference temperature at hour i. With this assumption, Eq. (II.93) can be rewritten as

$$Q_\tau'' = (g_0 - K_T)t_\tau + (g_1 - p_1K_T)t_{\tau-1} + (g_2 - p_2K_T)t_{\tau-2}$$

$$+ g_3t_{\tau-3} - p_1Q_{\tau-1}'' - p_2Q_{\tau-2}''.$$

If we normalize the cooling load from sources other than conduction (Q_i'') by the floor area of the room (A_f), we have

$$\left(\frac{Q_\tau''}{A_f}\right) = g_0^\star t_\tau + g_1^\star t_{\tau-1} + g_2^\star t_{\tau-2} + g_3^\star t_{\tau-3} - p_1\left(\frac{Q_{\tau-1}''}{A_f}\right) - p_2\left(\frac{Q_{\tau-2}''}{A_f}\right), \tag{II.99}$$

where

$$g_0^\star = (g_0 - K_T)/A_f,$$

$$g_1^\star = (g_1 - p_1K_T)/A_f,$$

$$g_2^\star = (g_2 - p_2K_T)/A_f, \text{ and}$$

$$g_3^\star = g_3/A_f. \tag{II.100}$$

Equation (II.99) is in the same form as Eq. (II.93) except that we are dealing with a normalized cooling load and normalized weighting factors. Equations (II.100) also apply to precalculated weighting factors where g_3 and p_2 are zero. The $g_i^\star$ are the tabulated, precalculated weighting factors; in use, values of the g_i are calculated by rearranging Eqs. (II.100) (Ref. 6). The units of the $g_i^\star$ are Btu/hr-ft^2-°F. By use of Eqs. (II.97) and (II.100), it can be shown that $g_0^\star + g_1^\star + g_2^\star + g_3^\star = 0$. This same normalization procedure is employed for the custom weighting factors in DOE-2. It allows consideration of the fact that the room conductance does change from hour to hour, owing to changing infiltration loads or external film coefficients which vary with wind velocity. It should be recognized, however, that, in general, this normalization procedure is only an approximation to the true variation of the air-temperature weighting factors with room conductance. Equation (II.98), which is the basis of the procedure, is exact for changes in conductance for varying infiltration, but it is only approximate for changes in conductance due to varying exterior film coefficients on walls (both delayed and quick walls). Thus, the normalization procedure should not be used to account for large changes in conductance from sources other than infiltration.

Another property inherent in the air-temperature weighting factors is a measure of the heat capacity of the room they represent. If a room with zero conductance is subjected to a pulse of energy, the walls and furniture of the room will come up to an equilibrium temperature after a sufficient time. If the total heat capacity of the room is mC_p, where m is the mass and C_p is the average heat capacity in Btu/lb-°F, then the temperature rise (Δt) is given by

$$\Delta t = \frac{q}{mC_p} ,$$

where q is the magnitude of the energy pulse in Btu. But the normalized weighting factors (g_i^*) represent a zero-conductance room. The heat capacity associated with the normalized weighting factors can be calculated from Eq. (II.93). The result is

$$mC_p = \frac{q}{\Delta t} = A_f \frac{3g_0^* + 2g_1^* + g_2^*}{1 + p_1 + p_2} . \tag{II.101}$$

In the case of precalculated weighting factors, where g_3^* and p_2 are zero, this reduces to

$$mC_p = A_f \frac{2g_0^* + g_1}{1 + p_1} . \tag{II.102}$$

As a check on the validity of the normalization procedure, mC_p calculated from Eqs. (II.101) or (II.102) can be compared with the total heat capacity of the room as calculated from the mass and heat capacity of the walls. The comparison is good if the actual room had a low conductance; however, for high conductance rooms, the two measures of heat capacity can be quite different. The results of the comparison reinforce the point that the variation of air-temperature weighting factors with room conductance, expressed by the normalization procedure, is only approximate.

2.3.4 Models Used in Weighting Factor Calculations

Various models are utilized throughout the weighting-factor calculation procedure. Heat transfer in furniture and its interaction with the remainder of a room are the subject of one model. The other models deal with the distribution of convective and radiative energy from different instantaneous heat-gain sources that are inputs for heat-gain weighting factors. The following sections describe the models used in DOE-2.

2.3.4.1 Furniture

As noted in previous discussions, furniture is treated like a wall during the weighting-factor calculation. A model has been constructed that allows Z-response factors to be calculated, a surface area to be assigned, and the amount of radiant energy striking the furniture to be estimated. The model is very simple; however, it accounts for the major effects of furniture on heat transfer in a room.

The important considerations in a model of furniture are:

1. total heat capacity,
2. surface area,
3. material properties, and
4. amount of radiant energy incident on the surface.

In DOE-2, some freedom in the choice of these parameters is given. The model assumes furniture is composed of slabs of material with specified properties. Two types of furniture are included, a light and a heavy type. Table II.5 lists the properties of each type. The Z-response factors were calculated assuming both surfaces of the slab exchange energy. The characteristic weight of each type of furniture is the mass of a 1-ft^2 slab.

The total heat capacity and surface area of the furniture are interrelated once the type of furniture (light or heavy) is chosen. The quantity of furniture is specified as the mass of furniture per unit floor area (f_{wa}) by using the FURN-WEIGHT keyword in the SPACE command or SPACE-CONDITIONS subcommand (in either an INPUT LOADS run or a LIBRARY-INPUT LOADS run) (Ref. 2). The surface area of the furniture, which is in addition to the area of the walls in the room, is calculated as

$$A_{fur} = A_f \frac{f_{wa}}{W_{ch}} , \qquad \text{(II.103)}$$

where A_f is the floor area and W_{ch} is the characteristic weight (in lb/ft^2 of floor area) for the type of furniture chosen. The use of response factors to describe furniture requires that, like walls, the mass be proportional to the surface area. For this same reason, the furniture surface area associated with radiative transport must be the same as the area for convection. In reality, some of the furniture area, such as internal surfaces, may be ineffective for radiative transport. The limitations of the model, however, cannot account for this condition. A limit has been placed on the furniture area such that $A_{fur} \leq A_f$. The limit prevents total domination of heat transfer in the room by the furniture; this occurs when the furniture area is of the same order of magnitude or larger than the total area of all walls in the room. The limit on area implies a limit on furniture mass also. This limit is relatively large, however, and should not restrict most uses of the furniture model. A technique of bypassing this limit on mass is discussed at the end of this section.

TABLE II.5

FURNITURE DATA

	Furniture Type	
	Light	Heavy
Slab Thickness (in.)	2	3
Thermal Conductivity (Btu/hr-°F-ft)	0.1	0.12
Density (lb/ft^3)	40	80
Specific Heat (Btu/lb-°F)	0.3	0.3
Characteristic Weight (lb/ft^2 floor area)	7	20
Z-Response Factors - Z_0	1.91606	3.79137
Z_1	-1.83648	-2.58534
Z_2	-0.07546	-0.65864
Z_3	-0.00392	-0.29885
Z_4	-0.00020	-0.13569
Common Ratio	0.05177	0.45404

The amount of radiant energy incident on the furniture from sources such as solar or lights is estimated by assuming that the furniture covers a certain fraction of the floor area. The fraction of the floor covered (F_{fa}) is input with the FURN-FRACTION keyword (Ref. 2). The total radiant energy that would strike that floor if no furniture were present (Q_{ft}) is distributed between the floor and furniture as

$$Q_{fur} = F_{fa} \, Q_{ft},$$

and

$$Q_f = Q_{ft} - Q_{fur} = (1 - F_{fa}) \, Q_{ft}, \qquad \text{(II.104)}$$

where Q_f and Q_{fur} are the total radiant energy incident on the floor and furniture, respectively. This portion of the model is certainly an approximation since the furniture can shield different amounts of the floor for different sources of radiant energy, and it may also shield some portions of side walls. The approximations are, however, consistent with other approximations made in the weighting-factor calculation.

For the weighting-factor calculation, furniture is treated like any other wall. The only difference is that furniture has no direct thermal connection with the exterior of the room; it can only exchange energy with the air and walls. The furniture area is used in the same manner as wall areas to estimate radiative view factors (see Sec. II.2.3.2.1).

If the furniture model available in DOE-2 is inappropriate in a particular situation, a user may construct his own model by use of the INTERIOR-WALL command (Ref. 2). Normally, interior walls are employed to separate two rooms in a building. However, during the LIBRARY-INPUT LOADS run, which generates custom weighting factors, it is possible to define an interior wall to be entirely within a room. This is done by specifying the wall to be next to the room it is defined to be in, i.e.,

```
ROOM-A = SPACE
      .
      .
      .
WALL-1 = INTERIOR-WALL
    NEXT TO ROOM-A
      .
      .
      .
      .
```

From this input, the wall appears once in the room (ROOM-A) with heat transfer from its inside surface. By use of the CONSTRUCTION command, the user can define the interior wall to match the properties of the furniture or other material to be modeled. This wall should be removed [from the LOADS input (see Ref. 2)] when conducting the actual load calculation because its mass and thermal connections to the remainder of the room are accounted for in the custom weighting factors for the room.

2.3.4.2 Solar Weighting Factors

Solar weighting factors represent a transfer function that relates the solar contribution to the cooling load to the instantaneous heat gain from solar energy entering the room through windows. The model for the solar weighting factors is quite simple. All solar energy entering the room is assumed to be radiant energy. (Solar energy entering the room after absorption in window glazing is grouped with energy entering the room by conduction.) The unit pulse employed for the weighting-factor calculation is distributed among the various walls (and furniture) as specified by values for the SOLAR-FRACTION keywords for walls in that room (Ref. 2). The energy incident on furniture is calculated as described in Sec. II.2.3.4.1. The total energy incident on each wall is assumed to be uniformly distributed over the entire wall area.

The user has complete freedom to distribute incident solar radiation in any manner he desires. However, only one set of solar weighting factors, for one energy distribution, is used during the loads calculation. Thus, the distribution should represent an average for the entire RUN-PERIOD (see BDL, Chap. II in Ref. 2).

Some of the solar radiation, entering the room through the windows, is reflected back out the windows. DOE-2 estimates the fraction of solar radiation lost in this manner by using a simple algorithm developed by F. Winkelmann of LBL (Ref. 22). The following definitions are employed:

α = solar absorptivity of opaque walls;

$\left.\begin{matrix}\rho_g\\ \tau_g\\ \alpha_g\end{matrix}\right\}$ = solar reflectivity, transmissivity, and absorptivity of the glazing, respectively;

A_g = area of the glazing;

A = total area of opaque walls and glazing;

η = A_g/A;

η' = $\eta(1 - \rho_g) = \eta(\tau_g + \alpha_g)$;

f_i = the fraction of absorbed solar radiation incident on the glazing from the inside that is conducted back into the room.

For a unit pulse of energy entering a room through the windows, the fraction α will be absorbed by the walls (including the furniture) and the fraction $(1-\alpha)$ will be reflected. The reflected portion can be (1) absorbed by the walls, (2) reflected by the walls or windows, (3) transmitted back out the windows, or (4) absorbed in the glazing. The fraction of the original pulse absorbed by the walls is $(1-\alpha)(1-\eta')\alpha$, the fraction reflected by the walls and windows is $(1-\alpha)(1-\eta')(1-\alpha)$, the fraction transmitted out the window is $(1-\alpha)\eta\tau_g$ and the fraction absorbed in the glazing is $(1-\alpha)\eta\alpha_g$. The amount absorbed and transmitted by the windows sums to

$$(1-\alpha)\eta' = (1-\alpha)\eta\tau_g + (1-\alpha)\eta\alpha_g,$$

and the total amount sums to

$$(1-\alpha) = (1-\alpha)\eta' + (1-\alpha)(1-\eta')\alpha + (1-\alpha)(1-\eta')(1-\alpha),$$

which is the fraction of the original pulse reflected in the first reflection. Of the amount absorbed in the glazing, the fraction f_i will be conducted back into the room and the fraction $f_o = (1 - f_i)$ will be conducted out. The quantity f_i can be estimated by considering the glazing as a series of thermal resistances that correspond to an interior film resistance (R_i), an air gap resistance (R_a), and an exterior film resistance (R_o). For this case

$$\alpha_g f_i = \alpha_{gi} \frac{(R_a + R_o)}{(R_a + R_o + R_i)} + \alpha_{go} \frac{R_o}{(R_a + R_o + R_i)},$$

where α_{gi} and α_{go} are the absorptivity of the inner and outer glazings, respectively. The amount of the original pulse reflected back into the room on the second reflection, $(1-\alpha)(1-\eta')(1-\alpha)$, can again be absorbed, reflected, or transmitted out the windows. The amount of energy absorbed in the room from all reflections can be written as the sum of two infinite sequences, that from the energy absorbed in the walls and that from the energy absorbed in the glazing and conducted back into the room. The result is

$$f' = \alpha + \alpha(1-\alpha)(1-\eta') + \alpha(1-\alpha)^2(1-\eta')^2 + \dots + (1-\alpha)\eta\, f_i\, \alpha_g$$

$$+ (1-\alpha)^2(1-\eta')\eta\, f_i\, \alpha_g + (1-\alpha)^3(1-\eta')^2\eta\, f_i\, \alpha_g + \dots ,$$

or evaluating the sums

$$f' = [\alpha + (1-\alpha)\eta\, f_i\, \alpha_g] \sum_{i=0}^{\infty} (1-\alpha)^i(1-\eta')^i$$

$$f' = \frac{\alpha + (1-\alpha)\eta\, f_i\, \alpha_g}{1 - (1-\alpha)(1-\eta')} . \qquad \text{(II.105)}$$

The value of α is set to 0.6 for all walls; ρ_g, α_g, and τ_g are all area averages for all glazing in the room. The amount of solar radiation lost by reflection back out the windows is incorporated in the solar weighting factors when they are calculated. Thus, for the solar weighting factors

$$\nu_i = f'\nu_i' ,$$

where ν_i' is the weighting factor calculated as described in Sec. II.2.3.3, and

$$\frac{\nu_0 + \nu_1 + \nu_2}{1 + w_1 + w_2} = ff' ,$$

where f is defined in Eq. (II.96). Values of f' are generally in the 0.9 to 1.0 range.

2.3.4.3 People and Equipment Weighting Factors

People and equipment weighting factors are represented by a transfer function, which relates the sensible energy contribution to the cooling load from people and equipment to the instantaneous heat gain from these sources. Sensible energy released by people or equipment can go directly to the air by convection or to surrounding walls (and furniture) by radiation. The model for people and equipment weighting factors is based on two items: (1) the relative amounts of radiant and convective energy released by the source, and (2) the distribution of the radiant energy on the surrounding walls and furniture. Only one set of weighting factors is required because both sources have similar properties.

ASHRAE recommends that the distribution of sensible energy from people in a room be taken as 70 percent radiant and 30 percent convective (Ref. 6). The physical basis for this split can be seen from a consideration of convective and radiant heat transfer coefficients. The radiant heat transfer coefficient can be estimated as

$$h_r = 4(\varepsilon)\sigma(T^3),$$

where ε is the emissivity for long-wavelength radiation (~ 0.9), σ is the Stephan-Boltzmann constant, and T is an average temperature in absolute units Ref. 19). For energy transfer between 100°F and 75°F, h_r is ~ 1.0 Btu/hr-ft^2-°F. The convective film coefficient (h_c) for a vertical cylinder with the same temperature difference is ~ 0.5 Btu/hr-ft^2-°F (Ref. 19). The fraction of energy released by radiation would be

$$\frac{h_r}{h_r + h_c} = 0.67.$$

This simplified calculation provides some insight into the basis for following the ASHRAE recommendation in this situation.

The variety of possible sources that fall under the heading of equipment makes simple and accurate models for sensible energy distribution from equipment nearly impossible. Source temperatures can range from near ambient for some electrical equipment up to 1000°F in food preparation areas. Also, the use of exhaust hoods over equipment can change the relative amounts of radiative and convective energy. As an approximation, the distribution of sensible energy from equipment is assumed to be the same as for people, i.e., 30 percent convective and 70 percent radiant.

The radiant energy from people and equipment is assumed to have a uniform intensity on all walls and furniture of a room. From this assumption, the total radiant energy incident on each wall is proportional to the wall area. The energy is assumed to be uniformly distributed over the entire wall area.

Sensible energy transferred to the air by convection in a given hour is counted entirely as cooling load in that hour. Thus, only the radiant energy released by a source can potentially be absorbed and stored by walls. The calculation of a sequence of cooling loads, which result from a unit pulse of radiant energy with uniform intensity on the walls of a room [$Q_u(i\Delta)$] was described in Sec. II.2.3.2. The cooling-load sequence, which defines the people and equipment weighting factors, is then

$$Q(0) = f_C + f_R\, Q_u(0), \quad \text{and}$$

$$Q(i\Delta) = f_R\, Q_u(i\Delta) \quad \text{for } i \geq 1, \tag{II.106}$$

where f_C and f_R are the fractions of the total energy that are released by convection and radiation, respectively. For people and equipment, $f_C = 0.3$ and $f_R = 0.7$. Equations (II.106) merely assign all the convective energy (f_C) to the first hour ($i = 0$), along with the energy released to the air from a pulse of magnitude f_R instead of a unit pulse. Energy released in subsequent hours also comes from a unit pulse of magnitude f_R. Final weighting factors are determined as normally done using the $Q(i\Delta)$ sequence (see Sec. II.2.3.3.2).

2.3.4.4 Lighting Weighting Factors

Lighting weighting factors represent a transfer function, which relates the lighting contribution to the cooling load to the instantaneous heat gain from lights in a room. Four types of general room lighting are available in DOE-2; the lighting type is specified at input by using the LIGHTING-TYPE keyword in the SPACE-CONDITIONS command (Ref. 2). The model for lighting weighting factors is similar to that for people and equipment. Each type of lighting source is assumed to release a constant fraction of its energy by radiation (f_R) and the remainder by convection to the air (f_C). The energy released by convection appears immediately as a cooling load. The radiant energy released by lights is assumed to have a uniform intensity on all walls. Once values of f_R and f_C are known for a given type of lighting, the calculation proceeds exactly as was described for people and equipment weighting factors.

The amount of radiant and convective energy released from lights depends on the type of lighting and on the ventilation associated with the lights (Ref. 23). No direct information was found for this energy split; however, for the four types of lights available in DOE-2, it is possible to estimate the relative amounts of radiative and convective energy from the value of the precalculated weighting factor ν_0 for those lights. Table II.6 lists the values of ν_0 for the four types of lights in DOE-2. This parameter, which represents the fraction of energy released that appears as a cooling load during the first hour, varies widely among the four types. However, there is some logic in the variation. For light types that are not vented to the plenum space above the ceiling (LIGHTING-TYPE=SUS-FLUOR or INCAND), ν_0 is smallest. The vented light without forced supply (LIGHTING-TYPE=REC-FLUOR-RV) has an intermediate value of ν_0. The largest value of ν_0 occurs for the light tyne with forced supply (LIGHTING-TYPE=REC-FLUOR-RSV). This pattern is consistent with the concept that lights with a large air flow should have large convective heat-transfer coefficients and thus have a large fraction of their energy transferred by convection.

It is possible to estimate the fraction of lighting energy that is radiative from the values of ν_0 for these lights. For this estimation, it is

TABLE II.6

LIGHTING DATA FOR WEIGHTING FACTOR CALCULATIONS

LIGHTING-TYPE	Description	Precalculated* v_0	f_R	f_c
SUS-FLUOR	Suspended fluorescent-unvented	0.53	0.67	0.33
REC-FLUOR-RV	Recessed fluorescent-vented to return air	0.59	0.59	0.41
REC-FLUOR-RSV	Recessed fluorescent-vented to supply and return air	0.87	0.19	0.81
INCAND	Incandescent	0.50	0.71	0.29

* v_0 is the same for light, medium, and heavy construction.

assumed that v_0 is composed of two parts, a portion that represents cooling load in the first hour from heat convected to the air and a portion that represents cooling load in the first hour from radiation incident on the walls. This can be written as

$$v_0 = (1 - f_R) + f_R v_0',$$

where f_R is the fraction of lighting energy that is radiative and v_0' represents the fraction of energy incident on the walls as radiation that appears as cooling load in the first hour. This formulation has the same basis as Eq. (II.106). The value of v_0' was estimated as 0.3, based on weighting-factor calculations for rooms similar to those used for the precalculated weighting factors. For this value of v_0', we have

$$f_R = 1.429\ (1 - v_0).$$

Table II.6 shows values of f_R and $f_c = (1 - f_R)$ calculated in this manner. The values of f_R for unvented lights (LIGHTING-TYPE = SUS-FLUOR or INCAND) is about the same as the radiant fraction for people and equipment. However, where both supply and return ventilation is through the light fixture (LIGHTING-TYPE = REC-FLUOR-RSV), most of the energy release of the lights is by convection.

2.3.4.5 Conduction Weighting Factors

Conduction weighting factors represent a transfer function, which relates the contribution to the cooling load from energy conducted into the room to the instantaneous heat gain from conduction. It is not immediately obvious that conduction weighting factors are needed to describe the disposition of conduction energy entering or leaving a room. Aside from furniture in the room, there appears to be no mechanism for delaying energy that enters through the interior wall surfaces. However, the need for conduction weighting factors actually arises from the difference between the true heat-transfer mechanism in the interior of a room and the mechanism modeled in DOE-2. During the load calculation in DOE-2, a combined radiative and convective film resistance (R_{RC}) is employed at the inside wall surfaces because its use greatly simplifies the calculation of heating and cooling loads. The value is input with the INSIDE-FILM-RES keyword associated with the LAYERS command (Ref. 2). The combined film resistance couples a wall surface to the room air for both radiation and convection; in reality, convection couples a wall surface to the room air, but for radiation a wall exchanges energy with other walls. Figure II.9 shows sketches of the DOE-2 model and a more realistic model for a two-wall room.

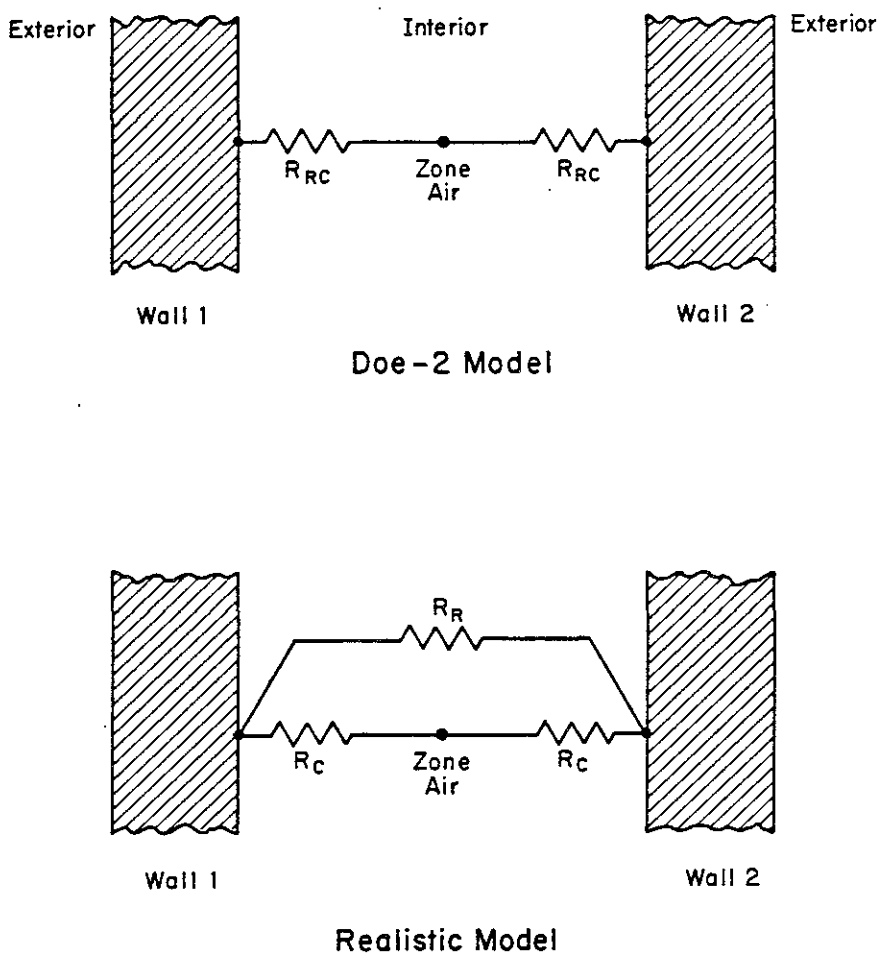

Fig. II.9. Models for energy transfer in the interior of a two-wall room.

In the sketch, R_C is the convective film resistance, R_R is the radiative resistance, and R_{RC} is the combined radiative and convective resistance, usually chosen such that

$$\frac{1}{R_{Rc}} = \frac{1}{R_c} + \frac{1}{R_R} . \qquad \text{(II.107)}$$

In the DOE-2 model, the only path for energy from an interior wall surface is to the zone air. Because the zone air represents a heat sink at a fixed temperature (the zone reference temperature) during the load calculation, there is no path for heat flow between walls in the DOE-2 model. The realistic model indicates that energy can flow between walls 1 and 2 if there is a temperature difference between the inside surfaces of the walls. Even though both walls are exposed to the same exterior and room air temperatures, they could exhibit different interior surface temperatures if they have different thermal properties or construction.

Even though the need for conduction weighting factors can be seen, a calculation technique is not obvious. Conduction weighting factors should represent the cooling-load sequence that results from a pulse of conduction energy at the interior wall surface. However, generating a pulse of conduction flux at interior wall surfaces for weighting-factor calculations would require temperature gradients in the walls. These temperature changes in the walls would effectively store some energy in the walls, as well as creating the conducting flux. During the weighting-factor calculation, it would not be possible to distinguish the energy initially stored in the walls from that in the conduction pulse. However, it is possible to estimate values of the conduction weighting factors by analyzing only the energy inside the interior wall surfaces in the same manner that was done for lighting, people, and equipment weighting factors. The analysis is based on the following assumptions.

1. Conduction-energy transfer from interior wall surfaces can occur by two modes, convection and radiation. The relative amounts of convective and radiative energy are constant.

2. Energy transfer by convection represents an immediate cooling or heating load.

3. Energy transfer by radiation can be analyzed by assuming that radiant energy from a wall has uniform intensity on all other walls in the zone. The cooling or heating loads from a pulse of this radiation, multiplied by the fraction of energy assumed to be radiant energy, represent conduction loads.

4. The unweighted conduction energy transfer rate was calculated using an appropriate value of the combined film resistance.

The process for calculating conduction weighting factors involves the specification of the fractions of energy assumed to be radiant (f_R) and convective (f_C). By the first assumption above, $f_R + f_C = 1$. The sequence of cooling loads obtained from a uniform radiant intensity on all of the room walls $[Q_u(i\Delta)]$ is the same sequence required for calculating weighting factors for lighting, people, and equipment. Based on the second and third assumptions noted above, the sequence of cooling loads used to calculate conduction weighting factors $[Q(i\Delta)]$ is computed as

$$Q(0) = f_C + f_R\, Q_u(0), \quad \text{and}$$

$$Q(i\Delta) = f_R\, Q_u(i\Delta), \quad \text{for } i > 0.$$

Final weighting factors are determined, as normally done, using the $Q(i\Delta)$ sequence (see Sec. II.2.3.3.2).

The last assumption requires the proper choice of R_{RC}. Equation (II.107) represents the correct choice, because it combines the two parallel heat-flow paths into a single path for each wall. Thus, the overall resistance for energy flow is correct for each wall. DOE-2 estimates R_R and R_C for the weighting-factor calculation so that Eq. (II.107) is satisfied when R_{RC} is the INSIDE-FILM-RES value for the wall. R_R is set at 1.111 and R_C is calculated from Eq. (II.107).

The final question is how best to estimate f_R and f_C for the conduction weighting factors. These fractions could be fixed as they were for lighting, people, and equipment weighting factors. However, since values of R_R and R_C are required for the weighting-factor calculation, f_R and f_C can be estimated from them. For one wall,

$$f_R = \frac{(R_R)^{-1}}{(R_R)^{-1} + (R_c)^{-1}} = \frac{R_c}{R_R + R_c} .$$

In cases where the R_R and R_C differ for the various walls in a room, an area average can be used

$$f_R = \frac{1}{A_T} \sum_{i=1}^{N} \frac{A_i\, R_{ci}}{R_{Ri} + R_{ci}} , \tag{II.108}$$

where R_{Ri}, R_{Ci} and A_i represent the radiative resistance, the convective resistance, and the area of wall i, respectively; N is the number of walls, and A_T is the total wall area (including furniture represented as a wall).

2.3.5 Interpolation of Precalculated Weighting Factors

The method for interpolating and extrapolating the precalculated (ASHRAE) weighting factors in DOE-2 is based on the relation between the z-transfer functions for some simple RC circuits and the weighting factors (Ref. 20). The heat-gain weighting factors (solar, lights, or conduction) are written in z-transfer-function notation as

$$T(z) = \frac{\nu_0 + \nu_1 z^{-1}}{1 + w_1 z^{-1}}, \tag{II.109}$$

where ν_0, ν_1, and w_1 are the weighting factors (Ref. 6). Similarly, the air-temperature weighting factors are written in z-transfer-function notation as

$$T(z) = \frac{g_0 + g_1 z^{-1} + g_2 z^{-2}}{1 + p_1 z^{-1}}, \tag{II.110}$$

where g_0, g_1, g_2, and p_1 are the weighting factors. The air-temperature weighting factors are calculated from normalized weighting factors (g_i^*) as a function of the size of the room and its total conductance (including infiltration). The equations are

$g_0 = A_f g_0^* + K_T$,

$g_1 = A_f g_1^* + p_1 K_T$, and

$g_2 = A_f g_2^*$,

where A_f is the floor area of the room and K_T is the total conductance (see Sec. II.2.3.3.2).

Weighting factors are available in DOE-2 for three typical rooms: light, medium, and heavy construction (Ref. 2). These construction types are quantified with a parameter called the floor weight, which represents the mass of construction material per unit floor area. The value is input with the FLOOR-WEIGHT keyword under the SPACE command (Ref. 2). Table II.7 lists the precalculated weighting factors in DOE-2. The heat-gain weighting factors were obtained from a publication of ASHRAE algorithms (Ref. 5), while the air-temperature weighting factors come from the ASHRAE 1977 Fundamentals Handbook (Ref. 6). The heat-gain weighting factors all use the same set of w_1's. The values of p1 (air-temperature weighting factors) for light and medium construction match the corresponding w_1; however, p1 for heavy construction is -0.93 compared to -0.91 for w_1. This difference represents an inconsistency between the heat-gain and air-temperature weighting factors because p_1 and w_1 should be the same for a given room.

Figure II.10 shows two simple RC circuits that can be used to analyze the precalculated weighting factors (Ref. 20). The quantity T_1 represents the room air temperature, T_2 is the exterior temperature, and, for Circuit B, T_s is the interior-wall surface temperature. The cooling load (heat flow to the air) is represented by $-Q_1$ in Circuit A and $-Q_1'$ in Circuit B; Q_s is a source term for the wall interior surface. The z-transfer function, which represents the variation in Q_1 for a change in T_1 in Circuit A, can be written as

TABLE II.7

PRECALCULATED WEIGHTING FACTORS IN DOE-2[a]

		Construction		
		Light	Medium	Heavy
Floor weight (lb/ft^2)		30	70	130
Solar				
v_0		0.224	0.197	0.187
v_1		-0.044	-0.067	-0.097
w_1		-0.820	-0.870	-0.910
Conduction				
v_0		0.703	0.681	0.676
v_1		-0.523	-0.551	-0.586
w_1		-0.820	-0.870	-0.910
Lighting				
SUS-FLUOR	v_0	0.530	0.530	0.530
	v_1	-0.350	-0.400	-0.440
	w_1	-0.820	-0.870	-0.910
REC-FLUOR-RV	v_0	0.590	0.590	0.590
	v_1	-0.410	-0.460	-0.500
	w_1	-0.820	-0.870	-0.910
REC-FLUOR-RSV	v_0	0.870	0.870	0.870
	v_1	-0.690	-0.740	-0.780
	w_1	-0.820	-0.870	-0.910
INCAND	v_0	0.500	0.500	0.500
	v_1	-0.320	-0.370	-0.410
	w_1	-0.820	-0.870	-0.910
Air temperature				
g_0^*		1.680	1.810	1.850
g_1^*		-1.730	-1.890	-1.950
g_2^*		0.050	0.080	0.100
p_1		-0.820	-0.870	-0.930

[a]The units of g_0^*, g_1^*, and g_2^* are Btu/hr-ft2-°F; the other weighting factors are dimensionless.

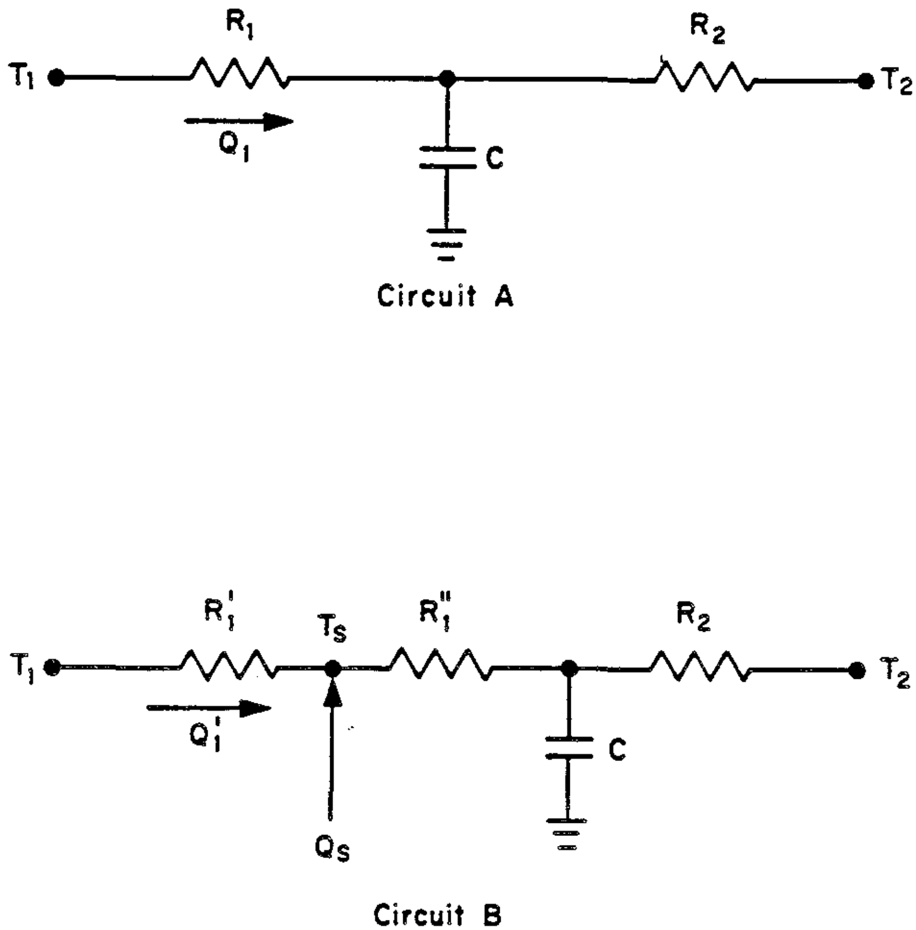

Fig. II.10. RC circuits used in precalculated weighting factor interpolation.

$$T(z) = \frac{a_0 + a_1\, z^{-1}}{1 + b_1\, z^{-1}} \; . \tag{II.111}$$

Similarly, the z-transfer function that represents the variation in Q_1' for a change in Q_S in Circuit B can also be written as Eq. (II.111). Physically, these are the processes represented by the air-temperature and heat-gain weighting factors. Thus, it is not unexpected that Eq. (II.111) is identical to Eq. (II.109) for the heat-gain weighting factors and close to Eq. (II.110) for the air-temperature weighting factors. Because of the additional term (g_2), Eq. (II.110) cannot be exactly represented by a simple RC circuit. For this analysis, g_1 and g_2 will be combined so that the air-temperature weighting factors are also in the form of Eq. (II.111).

All the precalculated weighting factors represent hypothetical rooms with zero conductance. For this reason $R_2 = \infty$ in Circuit A and Circuit B. In this special case, the circuit parameters can be related to the air-temperature weighting factors as

$$\begin{aligned}
\beta &= (R_1 C)^{-1}, \\
p_1 &= -\,e^{-\beta\Delta}, \\
g_0^* &= \frac{(1+p_1)\,C}{\Delta}, \\
C &= \frac{\Delta\, g_0^*}{1+p_1}, \\
R_1 &= \frac{1+p_1}{\Delta\beta\, g_0^*}, \text{ and} \\
g_0^* &+ g_1^* + g_2^* = 0.
\end{aligned} \tag{II.112}$$

For the heat-gain weighting factors we have

$$\begin{aligned}
\beta &= [C\,(R_1'+R_1'')]^{-1}, \\
w_1 &= -\,e^{-\beta\Delta}, \\
v_0 &= 1 - \frac{(1+w_1)\,(CR_1')}{\Delta}, \\
CR_1' &= \frac{\Delta\,(1-v_0)}{1+w_1}, \\
CR_1'' &= C\,(R_1'+R_1'') - \frac{\Delta\,(1-v_0)}{1+w_1}, \text{ and} \\
v_0 &+ v_1 = 1 + w_1.
\end{aligned} \tag{II.113}$$

In these equations, Δ is the time interval for the weighting factors, usually 1 hr. Separate values of R_1 and C can be determined from the air-temperature weighting factors [Eqs. (II.112)], but only the products $R_1'C$ and $R_1''C$ can be calculated from the heat-gain weighting factors [Eqs. (II.113)].

A number of assumptions are inherent in this correlation. It is assumed that the weighting factors for each type of construction (light, medium, or heavy) were computed for the same room so that the circuit parameters (R_1, R_1', R_1'' and C) for each type of construction are consistent. It is further assumed that the thermal capacitance (C) for each type of construction is independent of the type of weighting factor; that is, it is a function of floor weight only. It is also assumed that the total thermal resistance (R_1 in Circuit A) is independent of the type of construction. The relative values of R_1' and R_1'' (in Circuit B) are assumed to be independent of the type of construction; however, they are dependent on the type of weighting factor considered. The relative values of R_1' and R_1'' depend on how much of the source energy is assumed to go directly to the air as a cooling load. Solar weighting factors (R_1'/R_1'' large) represent the least energy going directly to the air, while REC-FLUOR-RSV lighting weighting factors (R_1'/R_1'' small) represent the most energy going directly to the air.

Table II.8 lists values of the circuit parameters computed from Eqs. (II.112) and (II.113). Values were computed for heavy construction for p_1 and w_1 equal to -0.91 and -0.93. It is evident that values of R_1 and the resistance ratios (R_1'/R_1'') for each heat-gain weighting factor are not exactly constant for the various types of construction; an average value will be used for the correlation. The values of R_1C and $(R_1' + R_1'')C$ are the same for each type of construction if p_1 and w_1 have the same value.

Figure II.11 shows a plot of C as a function of floor weight. Straight lines through the origin can be considered as lines of constant heat capacity, with

$$C = W\ Cp,$$

where W is the floor weight in lb/ft^2 and Cp is the heat capacity of the material in Btu/lb-°F. Lines for Cp = 0.1, 0.2, and 0.3 are shown. According to Mitalas, the light-construction room had an average Cp of 0.3 Btu/lb-°F (Ref. 24). Thus it is not surprising that C for this room falls almost on the Cp = 0.3 line. He also stated that the medium- and heavy-construction rooms had an average Cp of 0.2 Btu/lb-°F. On this basis, the value of $p_1 = -0.93$ would be correct for heavy construction. A value of $p_1 = -0.91$ would represent a room with Cp = 0.16 Btu/lb-°F. Values of p_1 and w_1 should be the same for a given room because these parameters primarily describe the long-term decay of any excitation. Based on the comments of Mitalas, taking both p_1 and w_1 to be -0.93 for heavy construction seems to be the most accurate choice. By doing this for the correlation, the heat-gain weighting factors for heavy construction will differ from the standard set in DOE-2.

The relationship between C and W will be taken as three linear segments, shown by the solid lines in Fig. II.10. Actually, values of R_1C were used instead of C in the fit. Table II.9 lists the equations for R_1C as a function of W along with average values of the parameters R_1 and (R_1'/R_1'') for the various types of weighting factors. One loose end remains: how best to estimate g_1^* and g_2^*. The analysis so far only estimates $g_1^* + g_2^* = -g_0^*$. It was observed that $g_2^*(1+p_1)$ is approximately constant for the three constructions. This empirical relation will be employed (see Table II.9).

TABLE II.8

CIRCUIT PARAMETERS FOR PRECALCULATED WEIGHTING FACTORS[a]

		Construction			
		Light	Medium	Heavy[b]	Heavy[c]
Floor weight (lb/ft^2)		30	70	130	130
Air temperature					
R_1		0.5399	0.5158	0.5158	0.5214
C		9.3333	13.9231	20.5556	26.4286
R_1C		5.0391	7.1808	10.6033	13.7798
Solar					
$R_1'C$		4.3111	6.1769	9.0333	11.6143
$R_1''C$		0.7279	1.0039	1.5700	2.1654
R_1'/R_1''		5.9227	6.1529	5.7537	5.3636
Conduction					
$R_1'C$		1.6500	2.4539	3.6000	4.6286
$R_1''C$		3.3891	4.7270	7.0033	9.1511
R_1'/R_1''		0.4869	0.5191	0.5140	0.5058
Lighting					
SUS-FLUOR	$R_1'C$	2.6111	3.6154	5.2222	6.7143
	$R_1''C$	2.4280	3.5654	5.3811	7.0654
	R_1'/R_1''	1.0754	1.0140	0.9705	0.9503
REC-FLUOR-RV	$R_1'C$	2.2778	3.1538	4.5556	5.8571
	$R_1''C$	2.7613	4.0270	6.0478	7.9225
	R_1'/R_1''	0.8249	0.7832	0.7533	0.7393
REC-FLUOR-RSV	$R_1'C$	0.7222	1.0000	1.4444	1.8571
	$R_1''C$	4.3169	6.1808	9.1589	11.9225
	R_1'/R_1''	0.1673	0.1618	0.1577	0.1558
INCAND	$R_1'C$	2.7778	3.8462	5.5556	7.1429
	$R_1''C$	2.2613	3.3346	5.0477	6.6368
	R_1'/R_1''	1.2284	1.1534	1.1006	1.0763

a The units of R_1, R_1', and R_1'' are $(Btu/hr\text{-}ft^2\text{-}°F)^{-1}$ and the units of C are $Btu/ft^2\text{-}°F$.

b For $p_1 = w_1 = -0.91$.

c For $p_1 = w_1 = -0.93$.

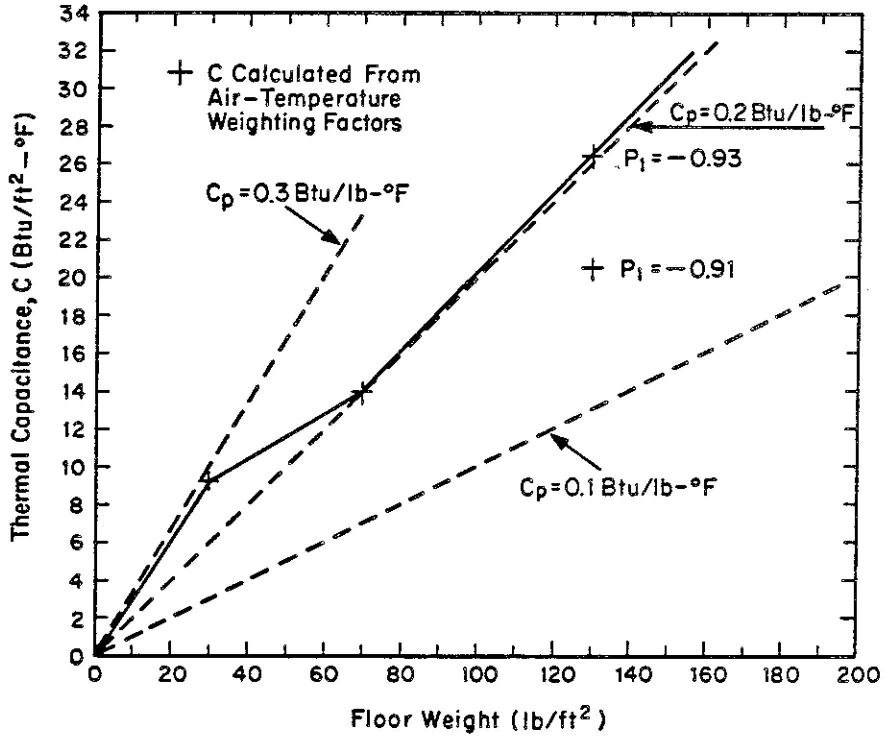

Fig. II.11. Thermal capacitance as a function of floor weight.

TABLE II.9

CORRELATION PARAMETERS

Air temperature	$R_1 = 0.5257$
Solar	$R_1'/R_1'' = 5.8131$
Conduction	$R_1'/R_1'' = 0.5039$
Lighting	
SUS-FLUOR	$R_1'/R_1'' = 1.0132$
REC-FLUOR-RV	$R_1'/R_1'' = 0.7825$
REC-FLUOR-RSV	$R_1'/R_1'' = 0.1616$
INCAND	$R_1'/R_1'' = 1.1527$

R_1C Correlation

$R_1C = 0.1680W$ for $W < 30$

$R_1C = 5.040 + 0.05354\,(W-30)$ for $30 \leq W \leq 70$

$R_1C = 7.1816 + 0.1100\,(W-70)$ for $W > 70$

g_2^* Correlation

$g_2^* = 0.009/(1+p_1)$

Using the data in Table II.9, weighting factors can be calculated for $\Delta = 1$ hr as

1. Given W, calculate R_1C;
2. $\beta = (R_1C)^{-1}$;
3. $p_1 = w_1 = -e^{-\beta}$;
4. $C = (R_1C)/R_1$;
5. $g_0^* = (1+p_1)C$;
6. $g_2^* = 0.009/(1+p_1)$; and
7. $g_1^* = -g_0^* - g_2^*$.

For each type of heat-gain weighting factor

8. $R_1'C = \dfrac{R_1C}{1 + (R_1'/R_1'')^{-1}}$,
9. $\nu_0 = 1 - (1+w_1)(R_1'C)$, and
10. $\nu_1 = 1 + w_1 - \nu_0$.

Figure II.12 shows a plot of three weighting factors (g_0^*, p_1 or w_1, and ν_0 solar) calculated from this correlation as a function of floor weight. Values used in DOE-2 for light, medium, and heavy constructions are shown for comparison. The behavior at low floor weights is consistent with custom weighting-factor calculations for very light rooms. This correlation gives reasonable weighting factors for floor weights in the range of 0.1 to 250 lb/ft^2. Inaccurate results occur below a floor weight of 0.1 lb/ft^2. No testing was done above 250 lb/ft^2.

2.3.6 Conclusion

The technique employed to find custom weighting factors has been described in Sec. II.2.3. Starting with z-transfer functions that describe heat-transfer processes in a room, a network was built up based on a heat balance of the inside surfaces of the walls. Transfer functions for the processes described by the heat-gain and air-temperature weighting factors were obtained by the time-step method. These z-transfer functions were approximated in a form that simplifies use in DOE-2.

Throughout the description of the weighting-factor calculation technique, a variety of assumptions and approximations have been discussed. The major assumptions inherent in the use of weighting factors are that the process modeled can be represented by linear differential equations and that the

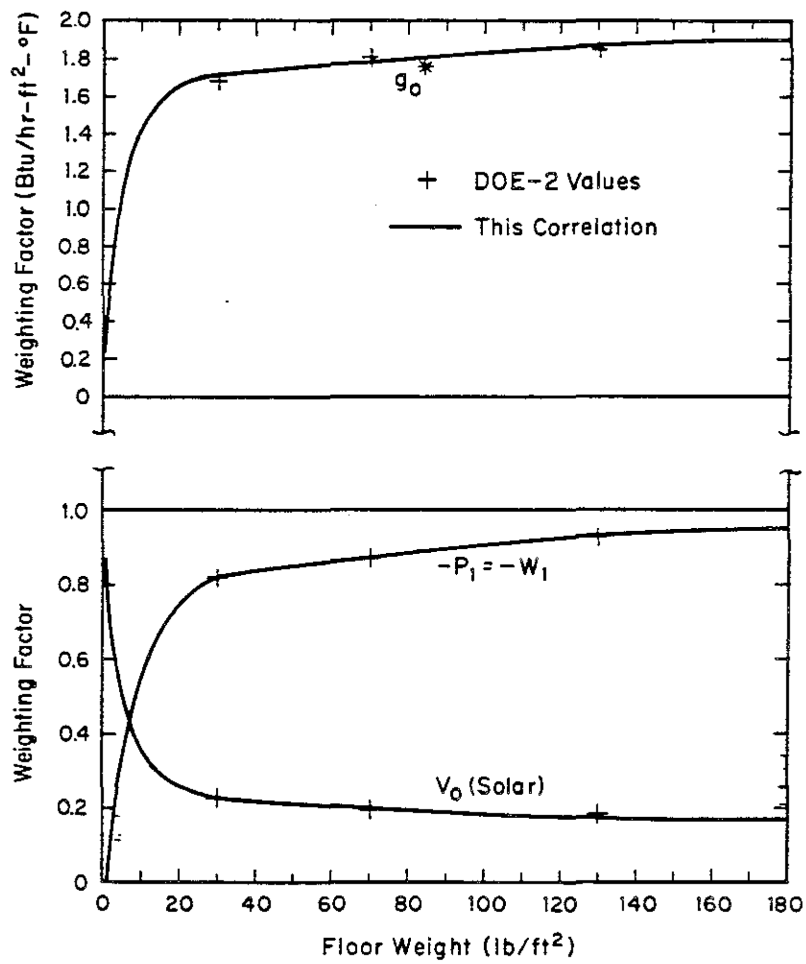

Fig. II.12. Typical weighting factors from this correlation.

coefficients in these equations are constant, i.e., not function of time or temperature. The assumption of linearity is necessary because the results from a variety of causes are determined independently and are summed to obtain the overall result. Thus, nonlinear processes, such as natural convection and radiation, must be approximated linearly. Generally, transfer-function methods are only used in situations where the transfer function is constant. Thus, system properties that define the weighting factors, such as heat transfer coefficients and radiation distributions, must also be constant. Methods have been proposed to bypass this limitation for z-transfer functions (Ref. 7), but they have not been implemented in DOE-2. A number of other assumptions have been mentioned throughout this description. They include items like radiation distributions in a room, radiative-convective energy splits from various sources, and properties for use in various models. Two of the most important approximations involved in the calculation are use of the time-step method (see Sec. II.2.2.2.4 and the requirement for a specific number of weighting factors (see Sec. II.2.3.3.1).

It is difficult to assess the effect of these approximations and assumptions on the final results from a building energy-analysis calculation since little has been done in the way of sensitivity analyses. Comparisons of hourly results from custom weighting-factor calculations in DOE-2 with measured values of air temperatures and heat-extraction rates in buildings and test cells have shown that DOE-2 can accurately predict the behavior of real structures. Unfortunately, there are no experimental measurements of weighting factors themselves to compare with calculated values. Although those measurements would be difficult, they could certainly be made with current technology. Any user of DOE-2 who expects highly accurate results from an analysis should be mindful of all the assumptions involved with precalculated and custom weighting factors, and should be wary if any of these assumptions are poor.

2.4. Weighting-Factor Subroutines in DOE-2

2.4.1 Introduction

The weighting-factor calculation method described in Sec. II.2.3 is incorporated into the Building Description Language (BDL) portion of DOE-2. There are two approaches to using Custom Weighting Factors:

1. Custom Weighting Factors can be automatically calculated and used for the current simulation by simply specifying FLOOR-WEIGHT = 0 in an INPUT LOADS run (see SPACE-CONDITIONS subcommand). These Custom Weighting Factors, however, are lost at the end of the current simulation.

2. Custom Weighting Factors can be calculated and saved in a library by doing a LIBRARY-INPUT LOADS run prior to the actual load calculation (Ref. 2).

The weighting-factor subroutines reside in a separate overlay. If a custom weighting-factor calculation is requested, subroutine WFMAIN (the weighting-factor control routine) is called by subroutine LDL. Figure II.13 shows a diagram of the weighting-factor subroutines as they are called during the calculation. A number of BDL subroutines for printing error messages or adjusting small-core field lengths have been omitted for clarity.

The weighting-factor subroutines shown in Fig. II.13 are described in the following sections. Each section consists of a summary or overview of the subroutine, a description of the algorithms used in the subroutine, and an outline of the calculation procedure employed. In addition to the custom weighting-factor subroutines, Sec. II.2.4.15 contains a description of subroutine WFASH, the subroutine that performs the interpolation and extrapolation of precalculated weighting factors.

The notation employed to present the weighting-factor algorithms in Sec. II.2.3 was based on historical usage in the literature and on mathematical convention. The notation used within the subroutines is generally different. Section II.2.4.16 has been included to relate the notation and variable names of Sec. II.2.3 to that used within the subroutines described in this section.

2.4.2 Subroutine WFMAIN

2.4.2.1 Summary

Subroutine WFMAIN is the main control routine for the weighting-factor calculation. It is called from subroutine LDL for any run that generates new library data as indicated by the LIBRARY-INPUT LOADS command (Ref. 2). If the library data are from MATERIALS, CONSTRUCTION or LAYERS commands, no weighting-factor calculations are performed; library data generated by these commands are merely written to the library file. For a custom weighting-factor generation run, weighting factors are calculated for each room or space where they were requested with a WEIGHTING-FACTOR keyword under the SPACE command. Data are assembled for the various walls and furniture in the space and rearranged for

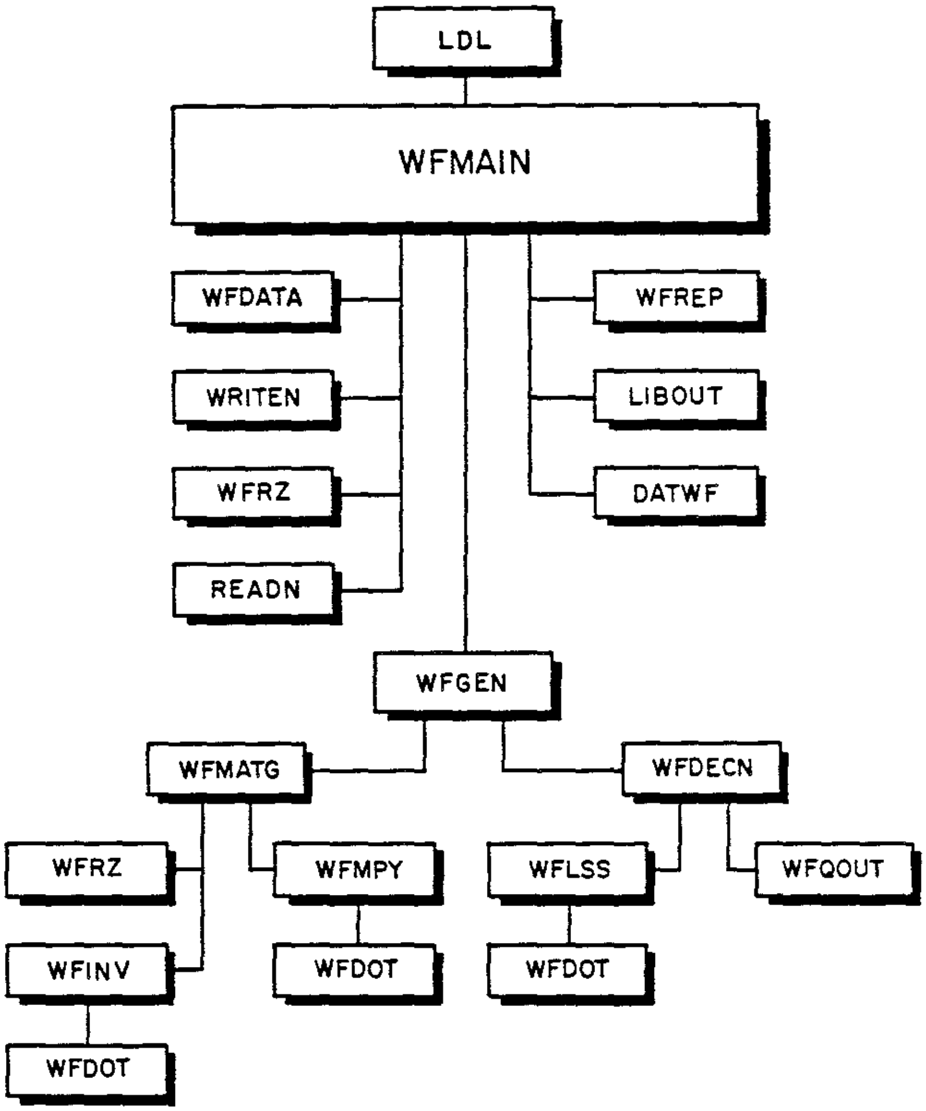

Fig. II.13. Weighting Factor Calculation Subroutines.

use during the weighting-factor calculation. Subroutine WFDATA and function WFRZ are called during this process. Subroutine WFGEN, which controls the actual weighting-factor calculation, is then called for the various kinds of weighting factors. Heat-gain weighting factors calculated are for solar radiation through windows, energy from people or equipment, general lighting, task lighting, and energy conducted into the space. Air-temperature weighting factors are also calculated. After calculation, the weighting-factor data are stored, written on the output file (subroutine WFREP), and written on the library file (subroutine LIBOUT).

There are a series of debug printouts of weighting-factor data throughout subroutine WFMAIN. These can be obtained by specifying the DUMP-OPTIONS = (DEBUG) keyword in the LOADS-REPORT command, which sets $IRERPT_{35}$ greater than zero.

There are a number of places in subroutine WFMAIN where preparation has been made for the Modified-Thermal-Balance calculation (LDSTYP=2). In this case, only air-temperature weighting factors are calculated and additional information is written on the standard file. This calculation has not been fully implemented in DOE-2 as yet.

2.4.2.2 Algorithms

The only algorithm employed in subroutine WFMAIN is the furniture area calculation [see Sec. II.2.3.4.1 and Eq. (II.103)].

2.4.2.3 Procedure

1. Rewind standard file and read data into AA_i array.
2. If no spaces in building, skip to 26.
3. Set pointers for data location in AA_i array for first space.
4. If custom weighting-factor calculation is not requested for this space, skip to 24.
5. Zero weighting-factor data arrays (V_{ij} and W_{ij}).
6. Count number of walls in space (NWP) including each exterior wall, window, door, interior wall, and underground wall as a separate wall.
7. If there are two or more opaque walls, skip to 9.
8. Weighting factors cannot be calculated for a space with fewer than two opaque walls. Set error flag, print message and skip to 24.
9. If furniture in space, increase NWP by one.
10. Prepare data pointers and storage space in AA_i array for weighting-factor data.
11. If $IREPRT_{35} > 0$, print pointers.
12. Call subroutine WFDATA to set up data needed for weighting-factor calculation. Skip to 24 if error in WFDATA (IWFERR > 0).
13. Calculate floor area of space (FLRFUR). If no furniture, skip to 17.
14. If FLRFUR > 0, skip to 16.
15. Space has furniture, but no floor to estimate furniture area. Print message, set error flag, and skip to 24.
16. Calculate furniture area and set furniture film resistances.
17. If $IREPRT_{35} > 0$, print weighting-factor data.

18. Count number of delayed surfaces. If at least one in space, skip to 20.

19. Cannot calculate weighting factors if space has no delayed surfaces. Set error flag, print message and skip to 24.

20. Set parameters for type of weighting factor (KW) and number of weighting factors (NNU and NDE).

21. Call WFGEN to calculate weighting factors. If error during calculation, skip to 24.

22. Store weighting factors in AA_i array.

23. If $IREPRT_{35} > 0$, print weighting factors.

24. Reset pointers to next space. If this was not the last space, skip to 4.

25. Call WFREP for a library creation run (LDSTYP $\neq$ 2), or if $IREPRT_{35} > 0$, to print weighting-factor summary for all spaces.

26. If fatal errors occurred (IFATAL $\neq$ 0), return to calling subroutine.

27. For modified thermal-balance calculation (LDSTYP = 3), write data to standard file.

28. For a library creation run (LDSTYP = 2) with no fatal errors (IFATAL = 0), call LIBOUT to write data on library file.

29. Return to calling subroutine.

2.4.3 Block Data DATWF

2.4.3.1 Summary

DATWF is a data block routine that sets the values of a number of constants used in the weighting-factor calculation.

2.4.3.2 Algorithms

There are no algorithms employed in DATWF.

2.4.3.3 Procedure

The following constants are set.

Constant	Values
$FRIL_i$ (i = 1,4)	0.67, 0.59, 0.19, 0.71
RCONF	1.7

Constant	Values
RRADF	1.111
$CHWT_i$ (i = 1,2)	7.0, 20.0
$RZFUR_{i,1}$ (i = 1,5)	1.91606, -1.83648, -0.07546, -0.00392, -0.00020
$RZFUR_{i,2}$ (i = 1,5)	3.79137, -2.58534, -0.65864, -0.29885, -0.13569
$COMRF_i$ (i = 1,2)	0.051772, 0.4540407
RRADC	1.111
RCONC	1.753
RFILM	0.68
ABSW	0.6

2.4.4 Subroutine WFDATA

2.4.4.1 Summary

Subroutine WFDATA prepares the wall and window data required for a custom weighting-factor calculation. It is called for a specific room or space, surface areas, film coefficients, solar energy absorbed, and control flags are placed in one area of the AA_i array. The fraction of solar energy not reflected back out the window is also calculated here.

2.4.4.2 Algorithms

Calculations are performed in subroutine WFDATA to obtain film coefficients for the walls, the amount of solar energy absorbed by each wall and the fraction of incoming solar radiation that is not reflected back out the windows. In DOE-2, film resistance data are input in a different form for delayed and quick walls. For delayed walls, the INSIDE-FILM-RES keyword under the LAYERS command is used to input the combined radiative and convective film resistance for the wall (RIFR = AA_{MI+8}). The radiative film resistance is set as AA_{ISP+3} = RRADC = 1.111. The convective film resistance is calculated as

$$AA_{ISP+2} = \frac{1}{\left[\frac{1}{RIFR} - \frac{1}{RRADC}\right]} .$$

See Sec. II.2.3.4.5 for a discussion of this equation. If the value of RIFR input results in a negative convective film resistance, a caution message is printed and RIFR is set to 0.68. For quick interior walls, an overall U-value for the wall, including combined film coefficients on each surface, is input under the U-VALUE keyword in the CONSTRUCTION command (AA_{MP+7}). The radiative and convective film resistances on the inside surface of the quick wall are set as

$$AA_{ISP+3} = RRADC = 1.111, \text{ and}$$

$$AA_{ISP+2} = RCONC = 1.753,$$

which result in a combined film resistance of 0.68 = RFILM. If the overall thermal resistance of the wall $[R = (1/AA_{MP+7})]$ is such that AA_{ISP+6} = RW = (R - 2*RFILM) < 0.05, the interior wall is excluded from the calculation of solar, lighting, people/equipment, and conduction weighting factors. The UA value of the wall is, however, included in the air-temperature weighting-factor calculation. For quick exterior walls, quick underground walls, windows and doors, the U-VALUE keyword does not include the external film resistance. For these walls, if AA_{ISP+6} = (R - RFILM) < 0.05, AA_{ISP+6} is set to 0.05. The exterior combined film resistance of quick surfaces is set to $AA_{ISP+4} = 0.33$, which corresponds to the film resistance for a 5 mph wind speed.

The fraction of incoming solar radiation absorbed by a wall (AA_{ISP+5}) is input with the SOLAR-FRACTION keyword for that wall. For exterior walls with windows, this value applies only to the opaque portion of the wall. For exterior walls with doors, the solar absorbed is apportioned between the doors and wall according to their relative areas. The AA_{ISP+5} for all walls in a space are normalized so the sum is equal to the fraction of solar radiation not reflected back out the windows.

The fraction of solar energy not reflected back out the windows is calculated as described in Sec. II.2.3.4.2. The reflectivity of the glazing (RHOWT) and the fraction of absorbed solar radiation incident on the glazing from the inside that is conducted back into the room (FWT) are calculated as area-weighted averages for all glazing in the room. Data for the transmissivity (AA_{MR+16}), inner glazing absorptivity (AA_{MR+22}), and outer glazing absorptivity (AA_{MR+17}) of diffuse radiation are used for each window. The absorptivity of walls (ABSW) is assumed constant at 0.6.

Data for the weighting-factor calculation are stored in the AA_i array. There are nine pieces for each wall, stored as AA_{ISP} through AA_{ISP+8}, where ISP is a pointer identifying the wall. Furniture data are stored as the last wall if furniture is present in the space. Section II.2.4.16 identifies the data stored.

2.4.4.3 Procedure

1. Initialize general data for current space. Space data pointer (MZ) set in WFMAIN. Determine infiltration resistance (RINF).

2. Set radiation exchange matrix terms to 1.

3. If number of exterior walls in space is zero, skip to 22.

4. Increment surface counter and initialize data for this exterior wall. If this is a quick surface, skip to 6.

5. Set film resistances for delayed exterior wall. Print a caution if INSIDE-FILM-RES is outside acceptable range. Skip to 7.

6. Set film resistances and wall thermal resistance for this quick exterior wall.

7. Set surface type and floor flags.

8. If number of windows in this exterior wall is zero, skip to 14.

9. Increment window and surface counters. Set radiation exchange matrix terms for this wall and window to zero since they are coplaner.

10. Set film resistances and thermal resistance for this window.

11. Add window area to total window area sum for this space. Calculate glazing reflectivity (RHOWT) and fraction of absorbed solar radiation incident on the glazing from the inside that is conducted back into room (FWT). The glazing reflectivity for radiation incident on the inside of the window is assumed to be equal to the reflectivity for radiation incident on the outside of the window.

12. Reset pointer for next window. If there are more windows in this exterior wall, skip to 9.

13. Set radiation exchange matrix terms to zero for all pairs of windows in the same exterior wall.

14. Calculate fraction of incoming solar energy absorbed by this exterior wall.

15. If number of doors in this exterior wall is zero, skip to 21.

16. Increment surface counter. Set radiation exchange matrix terms for this wall and door to zero since they are coplaner.

17. Calculate fraction of incoming solar energy absorbed by door.

18. Set film resistances and thermal resistance for door.

19. Reset pointer for next door. If there are more doors in the exterior wall, return to 16.

20. Set radiation exchange matrix terms to zero for all pairs of doors in the same exterior wall.

21. Reset point for next exterior wall. If there are more exterior walls in this space, return to 4.

22. If number of interior walls in space is zero, skip to 30.

23. Initialize data for this interior wall. Set flag to indicate whether this interior wall was defined in the current space or next to it. If this is a quick surface, skip to 25.

24. Set film resistance for delayed interior wall. Print caution if INSIDE-FILM-RES is outside acceptable range. Set flag to get correct response for delayed interior wall defined next to this space. Skip to 28.

25. Calculate thermal resistance of this quick interior wall.

26. If thermal resistance is too small, exclude wall from calculation of solar, lighting, people/equipment, and conduction weighting factors and go to Step 23 if there are more interior walls in this space.

27. Set film resistances for this quick interior wall.

28. Set surface type and floor flags. Calculate fraction of incoming solar energy absorbed by interior wall.

29. Reset pointer for next interior wall. If there are more interior walls in this space, return to 23.

30. If number of underground walls in space is zero, skip to 36.

31. Initialize data for this underground wall. Calculate fraction of incoming solar energy absorbed by underground wall. Set radiative film resistance. If this is a quick surface, skip to 33.

32. Set convective film resistance for delayed underground wall. Print caution if INSIDE-FILM-RES is outside acceptable range. Skip to 34.

33. Set convective film resistance and thermal resistance for quick underground wall.

34. Set surface type and floor flags.

35. Reset pointer for next underground wall. If there are more underground walls, return to 31.

36. Set total number of walls in space. If this is not a custom weighting-factor calculation, skip to 40.

37. Calculate area-weighted reflectivity of windows in space and fraction of incoming solar radiation not reflected back out windows.

38. Apportion solar fractions to the walls according to the following procedures:

    a. If the sum of solar fractions, QTOT, is zero, apportion 0.6 to the floor and furniture, if present, and distribute the remainder, 0.4, to the other walls according to their respective areas. If there is no floor in the space, distribute a total solar fraction of 1.0 to the walls according to their respective areas.

b. If $0 < QTOT \leq 1.0$, and some solar fractions are zero, distribute 1-QTOT to the walls with zero solar fraction according to their respective areas.

c. If $QTOT > 1.0$ and some solar fractions are zero, print error message.

d. If $QTOT > 0$ and no solar fraction is zero, print a caution message if $QTOT < 0.9$ or $QTOT > 1.1$; multiply each solar fraction by 1/QTOT so that their sum becomes 1.0.

39. Multiply the solar fractions determined in Step 38 by the fraction of incoming solar radiation that is not reflected back out the windows.

40. Return to calling routine.

2.4.5 Subroutine WFGEN

2.4.5.1 Summary

Subroutine WFGEN controls the calculation of the cooling-load sequence resulting from a pulse of energy or a pulse in air temperature (subroutine WFMATG) and the reduction of this cooling-load sequence to the weighting factors (subroutine WFDECN). The air-temperature weighting factors are normalized in this subroutine. Cooling-load sequences are printed if so requested.

2.4.5.2 Algorithms

The only algorithms employed in WFGEN are for normalization of the air-temperature weighting factors as described in Sec. II.2.3.3.2. The conductance of the room or space (CONN) is calculated according to Eq. (II.97) and the weighting factors are normalized as described by Eq. (II.100).

2.4.5.3 Procedure

1. The calling sequence sets the type of weighting factor (IWFT) and the number of numerator (NNU) and denominator (NDE) weighting factors wanted.

2. Initialize parameters.

3. If $IREPRT_{35}$ is not 1, skip to 5.

4. Print an identification of the type of weighting factor.

5. Call WFMATG.

6. If an error occurred, return to calling subroutine.

7. If $IREPRT_{35}$ is zero, skip to 9.

8. Print cooling-load sequence.

9. Set parameters and call WFDECN.

10. If the determinant is less than 10^{-12}, reduce the number of weighting factor terms and try deconvolution a second time; if this is already a second try, print an error message and return to the calling subroutine.

11. Set parameters and return to calling subroutine if this is a heat-gain weighting-factor calculation.

12. Normalize air temperature weighting factors.

13. Return to calling subroutine.

2.4.6 Function WFRZ

2.4.6.1 Summary

This function determines the correct response factor for a wall for use during the weighting-factor calculation.

2.4.6.2 Algorithms

For delayed surfaces, the value of the proper Z response factor is returned if the wall was defined in the space (room) of interest (see Sec. II.2.3.2.1). The X response factor is returned if the wall was defined in the adjacent space. For quick surfaces, the first response is calculated from the thermal resistance of the wall. All other response factors are zero for this wall (see Sec. II.2.3.2.1). For furniture, the proper furniture response factor calculated for the model furniture is returned.

2.4.6.3 Procedure

1. This function is called with the wall number (j) and the response factor number (k) desired. The result is returned as WFRZ.

2. Initialize WFRZ and wall pointers.

3. Set pointer (IXORG) for Z response factors.

4. Skip to 8 for delayed surface in this space.

5. Skip to 9 for quick surfaces.

6. Skip to 10 for furniture.

7. Delayed wall in adjacent space. Set pointer.

8. Determine proper response factor for delayed wall. Skip to 11.

9. Determine proper response factor for quick wall. Skip to 11.

10. Determine proper response factor for furniture.

11. Return to calling routine.

2.4.7 Subroutine WFREP

2.4.7.1 Summary

Subroutine WFREP prints a summary of the weighting factors calculated during a LIBRARY-INPUT LOADS run. This summary is also printed in an INPUT LOADS run if the user specified VERIFICATION = (LV-K) in the LOADS-REPORT instruction.

2.4.7.2 Algorithms

No calculational algorithms are employed in WFREP. For each space for which weighting factors have been calculated, the space name in a LIBRARY-INPUT LOADS run, the name of the weighting factors assigned with the WEIGHTING-FACTOR keyword, and the values of the weighting factors are listed on the output file. In an INPUT LOADS run, WFREP prints custom weighting factors for all those spaces where the user has specified FLOOR-WEIGHT = 0 or WEIGHTING-FACTOR = U-name, and prints precalculated weighting factors for those spaces where the user has specified FLOOR-WEIGHT ≠ 0.

2.4.7.3 Procedure

1. Initialize pointer variables and identify each space for which weighting factors were calculated. Skip to Step 3 if this is <u>not</u> a LIBRARY-INPUT LOADS run or if this <u>is</u> a LIBRARY-INPUT LOADS run and weighting factors are to be calculated for one or more spaces.

2. No weighting factors were calculated in a LIBRARY-INPUT LOADS run. Print message and return to calling routine.

3. Print page heading and title. If this is not the first page, print continuation identification.

4. Print space names and weighting-factor names, up to seven per page.

5. Print solar, general lighting, task lighting, people and equipment, conduction, and air-temperature weighting factors.

6. If output completed, return.

7. Skip to 3.

2.4.8 Subroutine WFMATG

2.4.8.1 Summary

Subroutine WFMATG sets up the network parameters describing a room or space and calculates the sequence of cooling loads resulting from a unit pulse of energy or air temperature. The basis for this calculation and the equations employed are discussed in Sec. II.2.3.2.

2.4.8.2 Algorithms

There are a number of algorithms employed in WFMATG. The relative amount of solar energy absorbed by each wall was determined in WFDATA, however, furniture was not included. Here, the solar energy that would be absorbed by the floor of a room or space if no furniture were present is apportioned between the floor and furniture as described in Sec. II.2.3.4.1, Eq. (II.104). The radiation conductors between each pair of walls are calculated as described in Sec. II.2.3.2.1 (Eq. II.65).

The next step in the calculation is to set up the NWALL by NWALL $\tilde{C}$ matrix of Eq. (II.69), Sec. II.2.3.2.3, where NWALL is the number of walls in the space including furniture. This matrix is inverted by subroutine WFINV.

For the air-temperature weighting factors, the room air temperature (TR) is set to 1 for the first hour and zero for subsequent hours. All radiant source terms on the walls are zero for this calculation [see Eqs. (II.75)]. For the heat-gain weighting factors, TR is zero and the radiant source terms on the walls are chosen according to the models described in Sec. II.2.3.4.2, II.2.3.4.3, II.2.3.4.4, and II.2.3.4.5 [see Eqs. (II.74)]. The cooling load for the first hour is calculated according to Eq. (II.80), while for subsequent hours the recursion relation, Eq. (II.82), is employed.

The heat-gain weighting factors for lighting, conduction, and people and equipment use a uniform radiant intensity on all walls as source terms. The cooling-load sequence resulting from this source is only determined once. The cooling-load sequence for each type of weighting factor is calculated according to Eq. (II.106). The fraction of total energy released by convection and radiation for each type of weighting factor is determined as noted in Sec. II.2.3.4.3 for people and equipment, in Sec. II.2.3.4.4 and Table II.6 for lighting, and in Sec. II.2.3.4.5, Eq. (II.108) for conduction.

2.4.8.3 Procedure

1. Subroutine WFMATG is called with the type of weighting factor required (IWFT) and a parameter to indicate whether recalculation of matrix terms is necessary (IRECAL).

2. Initialize parameters. If matrix coefficients need not be recalculated, skip to 12.

3. Calculate total area of all walls in space, excluding furniture.

4. If no furniture in the space, skip to 6.

5. Determine total solar absorbed by all floor sections. Split this between furniture and floor using PFA.

6. If infiltration resistance (RINF) is zero, set to large value so no infiltration is allowed.

7. Calculate the radiation conductors between all pairs of walls. Store as AA_{IJ1}, where IJ1 is a single pointer locating the $NWALL^2$ values. Sum all radiation conductors associated with each wall in preparation for calculation of matrix coefficients. Move the amount of solar energy absorbed by each wall (AA_{ISP+5}) into the source term array (AA_{ISP+8}).

8. Calculate the individual elements of the matrix $\tilde{C}$. Store as AA_{IJ2}, where IJ2 is a single pointer locating the $NWALL^2$ values.

9. Call WFINV to invert the $\tilde{C}$ matrix.

10. If the determinant of $\tilde{C}$ is greater than 10^{-12}, skip to 12.

11. The matrix $\tilde{C}$ is singular or near singular. Set error flag, print message and return to calling routine.

12. For solar weighting factors, skip to 13. For air-temperature weighting factors, skip to 14. For all other weighting factors, skip to 15.

13. Set air temperature (TR) to zero. Print solar source terms if $IREPRT_{35} = 1$. Skip to 19.

14. Set air temperature to one. Set all source terms to zero. Print source terms if $IREPRT_{35} = 1$. Skip to 19.

15. If cooling-load sequence already determined for this space for radiant source terms of uniform intensity (IRECUN > 0), skip to 30.

16. Set air temperature to zero. Set radiant source terms (AA_{ISP+8}) equal to area fraction of each wall, not including furniture. If furniture is present, apportion radiant source term for floor between floor and furniture.

17. Calculate fraction of conduction flux through walls that leaves wall surface by radiation (FR) and convection (FC).

18. Print radiant source terms if $IREPRT_{35} > 0$.

19. Calculate cooling load for first hour [Eq. (II.80)]. Evaluate $B_m(0)$ according to Eq. (II.76) and store as $AA_{MWFB+I-1}$.

20. Call WFMPY to multiply the inverse of $\tilde{C}$, i.e., D_{im}, which is stored as AA_{MWFA+I}, by $B_m(0)$. The result is in $AA_{MWFX1+K}$, K = 1, NWALL.

21. If $IREPRT_{35} = 1$, print $AA_{MWFX1+K}$.

22. Calculate the cooling load and sum for all walls. Correct for infiltration and store as QS_1. Change sign convention for air-temperature weighting factors.

23. Set radiant source terms to zero.

24. Start calculation of cooling load for next hour.

25. Evaluate terms in Eqs. (II.82). Call WFMPY for matrix multiplication Store each walls cooling-load contribution as AA_{IL2} for use during subsequent hours calculations. Save as QS_L. Change sign convention for air-temperature weighting factors.

26. Check whether common ratio of successive cooling loads is sufficiently constant. Obtain at least 10 cooling loads. If change in common ratio is less than 10^{-4}, skip to 29.

27. Save last common ratio. If less than 50 cooling loads have been calculated, skip to 24.

28. Stop calculation at 50 hours.

29. If this calculation was for solar or air-temperature weighting factors, return to calling routine.

30. Calculate cooling loads for other weighting factors from cooling loads determined for a uniform intensity of radiation on the walls. Save uniform-intensity cooling loads as QUN_L. Set IRECUN = 1.

31. Skip to 32 for people and equipment cooling loads. Skip to 33 for lighting cooling loads. Skip to 34 for conduction cooling loads.

32. Calculate cooling loads for people and equipment. Return to calling routine.

33. Calculate cooling loads for lighting. Return to calling routine.

34. Calculate cooling loads for conduction. Return to calling routine.

2.4.9 Subroutine WFDECN

2.4.9.1 Summary

Subroutine WFDECN calculates a set of weighting factors from the sequence of cooling loads determined in WFMATG. The method used is described in Sec. II.2.3.3.1. A set of simultaneous linear equations relating the weighting factors to the cooling loads is solved for the weighting factors.

2.4.9.2 Algorithms

Subroutine WFDECN solves the set of simultaneous linear equations of Sec. II.2.3.3.1 [Eqs. (II.88) and (II.89)] for the weighting factors. A conventional linear equation solver, subroutine WFLSS, is employed. The equations are rearranged in matrix form ($\tilde{A}\tilde{X} = \tilde{B}$) as

$$\begin{aligned}
\nu_0 \qquad\qquad\qquad\qquad\qquad &= d_0. \\
\nu_1 \qquad - d_0 w_1 \qquad &= d_1. \\
\nu_2 - d_1 w_1 - d_0 w_2 &= d_2. \\
- d_2 w_1 - d_1 w_2 &= d_3. \\
\nu_0 + \nu_1 + \nu_2 - f\ w_1 - f\ w_2 &= f\ .
\end{aligned}$$

The coefficient matrix, A_{ij}, is

$A_{1,j}(j = 1,5) = 1, 0, 0, 0, 0;$

$A_{2,j}(j = 1,5) = 0, 1, 0, -d_0, 0;$

$A_{3,j}(j = 1,5) = 0, 0, 1, -d_1, -d_0;$

$A_{4,j}(j = 1,5) = 0, 0, 0, -d_2, -d_1;$ and

$A_{5,j}(j = 1,5) = 1, 1, 1, -f, -f.$

The right-hand-side vector, B_i, is

$B_i(i = 1,5) = d_0, d_1, d_2, d_3, f.$

The unknown vector, X_i, contains the weighting factors, i.e.,

$X_i(i = 1,5) = \nu_0, \nu_1, \nu_2, w_1, w_2.$

The air-temperature weighting factors require one additional equation. The technique for rearrangement into matrix form is analagous to that for cooling-load weighting factors.

2.4.9.3 Procedure

1. Subroutine WFDECN is called with the type of weighting factor (KW) and the number of numerator (NNU) and denominator (NDE) terms requested. The values of the weighting factors (V_i and W_i) are returned.

2. The common ratio (CR) and total energy content (FC) of the cooling-load sequence are calculated.

3. Evaluate the coefficients of the A_{ij} matrix. Set the right-hand-side terms into the V_i array.

4. Call WFLSS. The values of the weighting factors are returned in the V_i array. If the determinant of the A_{ij} matrix (DETERM) is greater than zero, skip to 6.

5. The weighting factors cannot be determined since A_{ij} is singular (see Sec. 2.3.3.1). Set error flag, print message, and return to calling routine.

6. Store weighting factors in the V_i and W_i array.

7. If $IREPRT_{35} < 1$, skip to 10.

8. Print weighting factors. Calculate and print the fraction of the incoming energy that shows up as a cooling load for heat-gain weighting factors (F) [see Eq. (II.96)].

9. Call subroutine QOUT to calculate and print the cooling-load sequence calculated from the weighting factors.

10. Return to calling routine.

2.4.10. Subroutine WFQOUT

2.4.10.1 Summary

Subroutine WFQOUT calculates the cooling-load sequence that would result from a unit pulse applied to the weighting factors. This sequence can be compared with the cooling-load sequence that determined the weighting factors. The results are printed.

2.4.10.2 Algorithms

The cooling loads that result from a unit pulse applied to the weighting factors are calculated. Either Eq. (II.91) or (II.93) are employed. For the heat-gain weighting factors [Eq. (II.91)], $q_0 = 1$ and all other q_i are zero. The cooling loads (Q_τ) are calculated by repeated application of Eq. (II.91) for $\tau = 0, 1, 2$, etc.

2.4.10.3 Procedure

1. Subroutine WFQOUT is called with the number of weighting factors (NNU and NW), the number of hours to do the calculation (NQT) and the weighting factors (V_i and W_i).

2. Start calculation for first hour.

3. For next hour, set calculated cooling load (Q_i) to zero.

4. Sum contribution to Q_i from the V_i and W_i.

5. If NQT hours not finished, skip to 3.

6. Print Q_i ($i = 1$, NQT).

7. Return to calling routine.

2.4.11 Subroutine WFINV

2.4.11.1 Summary

WFINV finds the inverse of an IN by IN matrix (A_{ij}).

2.4.11.2 Algorithms

Elementary row transformations are employed to reduce the matrix A_{ij} to the canonical form of the identity matrix. The same transformations, when applied to the rows of the identity matrix, produce the inverse of A_{ij}. Partial pivoting for the largest diagonal elements is done. Inner products are accumulated in double precision.

The matrix is singular if, after partial pivoting for the largest diagonal elements, any diagonal element is zero. The calculation terminates and DET is set to zero if this occurs.

WFINV is a slightly modified version of the Los Alamos National Laboratory subroutine MATINV (Ref. 25).

2.4.12 Subroutine WFLSS

2.4.12.1. Summary

Subroutine WFLSS solves the non-singular matrix equation $\tilde{A}\tilde{X} = \tilde{B}$.

2.4.12.2 Algorithms

The method employed is LU decomposition with partial pivoting and double-precision accumulation of inner products using WFDOT (Ref. 21). WFLSS is a slightly modified version of the Los Alamos National Laboratory subroutine LSS (Ref. 25).

2.4.13 Function WFDOT

2.4.13.1 Summary

Function WFDOT returns the dot product or inner product of two vectors. The inner product is accumulated in double precision.

2.4.13.2 Algorithms

Subroutine WFDOT is a slightly modified version of the Los Alamos National Laboratory subroutine DOTPRO (Ref. 25). The inner product of two vectors, X_i and Y_i, is defined as

$$WFDOT = \sum_{i=1}^{N} X_i \; Y_i ,$$

where N is the number of element in the arrays X_i and Y_i.

2.4.14 Subroutine WFMPY

2.4.14.1 Summary

Subroutine WFMPY multiplies two matrices to form a third, $\tilde{A}\tilde{B} = \tilde{C}$.

2.4.14.2 Algorithms

If $\tilde{A}$ is an nxm matrix and $\tilde{B}$ is an mxk matrix, the product matrix, $\tilde{C}$ is an nxk matrix. The elements of C are computed in double precision as the inner product of a row of A with a column of B using WFDOT. This subroutine is a slightly modified version of the Los Alamos National Laboratory subroutine MATMAPY (Ref. 25).

2.4.15 Subroutine WFASH

2.4.15.1 Summary

Subroutine WFASH selects the correct set of precalculated weighting factors for a room or space and stores them in a data array associated with that space. If the value input under the FLOOR-WEIGHT keyword is exactly 30, 70 or 130 lb/ft^2, ASHRAE precalculated weighting factors for light, medium, or heavy construction are selected. Any other value results in an interpolation as described in Sec. II.2.3.5.

2.4.15.2 Algorithms

The interpolation and extrapolation of the precalculated weighting factors is performed as described in Sec. II.2.3.5. The ASHRAE precalculated weighting factors are stored in the variables CONDWF, LITEWF, SOLWF, ATWF, and W1. The parameters necessary for interpolation are stored in the variables R1, R1P, GP, and in the equation defining C. The variable RIP is defined as

$$RIP = \frac{R_1}{1 + (R_1^{'}/R_1^{''})^{-1}} .$$

2.4.15.3 Procedure

1. Subroutine WFASH is called with the floor weight (FLRWT) and the lighting type (ILT) for the space.

2. Store zeros in the array that will contain the weighting factors, AA(IAX+1) to AA(IAX+31).

3. IF FLRWT is exactly 30, 70 or 130, skip to 6.

4. Interpolation of weighting factors. Calculate parameters dependent on floor weight.

5. Calculate weighting factors. Return to calling routine.

6. Set index for proper construction type (IW).

7. Store precalculated weighting factors.

8. Return to calling routine.

2.4.16 Notation and Variable Names

The notation employed to present the weighting-factor algorithms in Sec. II.2.3 was based on historical usage in the literature and on mathematical conventions. The notation used within the subroutines is based on programming convenience and is generally different than that used in the literature. This section has been included to provide a tie between the notation and variable names of Sec. II.2.3 and those in the subroutines.

Many of the variables used in DOE-2 are stored in a single common-block array, called the AA_i array for real variables and the IA_i array for integers. Data are assessed by saving pointers to the location within the array where the data reside. Data stored in the AA_i or IA_i array are generally variables that must be communicated between a number of different subroutines. Data used only within individual subroutines are usually assigned simple variable names.

Data in the AA_i or IA_i array are accessed by defining pointers to where in the array the data are stored. Some of the pointers are used in other sections of DOE-2 in addition to the weighting-factor calculation. The identification of specific items accessed with these pointers can be obtained as output from the EDTSRC program, which is used to prepare the file EDTT. For example, MX is the exterior-wall data pointer and AA_{MX+25} is the value input under the SOLAR-FRACTION keyword for this wall. The identification of these variables will not be repeated here. Other pointers are used only within the weighting-factor calculation routines. Specific variables referenced by these pointers are identified here. Table II.10 lists the AA_i and IA_i array pointers.

Variable names not in the AA_i or IA_i array are listed in Table II.11. In some cases these variables are communicated between subroutines and in others they are used entirely within specific subroutines.

TABLE II.10

POINTERS FOR AA_i AND IA_i ARRAY

Pointer	Section II.2.3 Variable	Description
IJ1	G_{ij}	Storage for radiation conductors between walls - see Eq. (II.65). $NWALL^2$ variables.
IJ2	C_{ij} and D_{ij}	Storage for matrix elements - see Eq. (II.69). $NWALL^2$ variables.
ISP+L (L=0 to 8)	-	Storage for 9 variables for each wall in a space. ISP = MWFX + (I-1)*LENWF, where I is the wall number.
ISP	A_i	Wall area for wall i.
ISP+1	-	Surface type flag.
ISP+2	$(h_{ci})^{-1}$	Inside convective film resistance.
ISP+3	$(4\varepsilon_i \sigma T_R^3)^{-1}$	Inside radiative film resistance.
ISP+4	-	Outside combined film resistance.
ISP+5	-	Fraction of incoming solar radiation absorbed by inside wall surface.
ISP+6	-	Surface to surface thermal resistance of a quick wall.
ISP+7	-	Surface type flag.
ISP+8	Q_{Si}	Fraction of radiation pulse absorbed by wall inside surface.
LENWF	-	Length of wall storage = 9.
MD	-	Door pointer.[a]
MI	-	Interior wall pointer.[a]
MP	-	Wall property pointer.[a]
MR	-	Glazing property pointer.[a]
MU	-	Underground wall pointer.[a]

TABLE II.10 (Cont.)

Pointer	Section II.2.3 Variable	Description
MWF	ν_i, w_i, g_i^*, p_i	Weighting-factor storage pointer.[a]
MWFA	See IJ2	Storage for NWP^2 variables.
MWFB	B_i	Storage for NWP variables.
MWFC	–	Storage for NWP variables.
MWFDET	–	Storage for NWP variables.
MWFG	See IJ1	Storage for NWP^2 variables.
MWFGS	$\sum_{i}^{NWP} G_{ij}$	Storage for NWP variables.
MWFQW	Q_i	Storage for 50*NWP variables.
MWFX	See ISP	Storage for NWP*LENWF variables.
MWFX1	–	Storage for NWP variables.
MWI	–	Window property pointer.[a]
MX	–	Exterior wall pointer.[a]
MZ	–	Zone or space pointer.[a]

[a]See output of EDTSRC program.

TABLE II.11

WEIGHTING FACTOR VARIABLES

Program Variable	Section II.2.3 Variable	Description
ABSW	–	Solar absorptivity of inside wall surface – see DATWF.
AT	–	Total surface area of all walls in a space (WFMATG).
ATNW	–	Total surface area of opaque walls (WFDATA).
ATWF	–	Precalculated air-temperature weighting factors (WFASH).
ATWIN	–	Total window area in a space (WFDATA).
AWTW	–	Total window area in a wall (WFDATA).
C	C	Parameter used in precalculated weighting-factor interpolation (WFASH) – see Sec. II.2.3.5.
CFM	V_{in}	Infiltration in cfm (WFDATA).
$CHWT_i$	W_{CH}	Characteristic weight of furniture of type i – see DATWF and Sec. II.2.3.4.1.
$COMRF_i$	–	Common ratio for response factors for furniture of type i – see DATWF and Sec. II.2.3.4.1.
CONDWF	–	Precalculated conduction weighting factors (WFASH).
CONN	K_T	Conductance of space – see Sec. II.2.3.3.2.
CRS, CRSV	CR_i	Common ratio of a cooling-load sequence QS_i – see Sec. II.2.3.3.1.
F	f	$(\nu_0 + \nu_1 + \nu_2)/(1 + w_1 + w_2)$ in WFDECN only – see Sec. II.2.3.3.2.
FC	f_c	Fraction of energy entering a space by conduction that leaves a wall by convection to the air (WFMATG only) – see Sec. II.2.3.4.5.
FLAR	–	Floor area of space input under AREA keyword.

TABLE II.11 (Cont.)

Program Variable	Section II.2.3 Variable	Description
FLRFUR	–	Floor area of space as sum of walls with TILT = 180° (WFMAIN).
FLRWT	–	Value input under FLOOR-WEIGHT keyword for space (WFASH).
FR	f_R	1 – FC.
FREM	f'	Fraction of solar energy entering a space that is not reflected back out the windows – see Sec. II.2.3.4.2.
$FRIL_i$	–	Fraction of lighting energy that leaves by radiation for lighting type i – see Sec. II.2.3.4.4.
FWA	–	Value input under FURNITURE-WEIGHT keyword.
FWT	f_i	Fraction of reflected solar radiation incident on inside of glazing that is conducted out of the space – see Sec. II.2.3.4.2.
GP	$g_2^*/(1 + P_1)$	Parameter used in precalculated weighting-factor interpolation (WFASH) – see Sec. II.2.3.5. Value is 0.009.
IFATAL	–	Fatal error flag.
IFRN	–	Furniture flag; 1 for furniture in space.
IFUR	–	Furniture type; 1 for light and 2 for heavy.
IL	–	Lighting type; 1 to 4.
ILT	–	Lighting type; 1 to 4 (WFASH only).
IRECAL	–	Flag controlling calculation of matrix terms in Eq. (II.69) (WFMATG).
IRECUN	–	Flag indicating whether cooling-load sequence calculated for uniform radiant intensity on walls (WFMATG).
$IREPRT_{35}$	–	Debug print flag.
IWFERR	–	Error flag.

TABLE II.11 (Cont.)

Program Variable	Section II.2.3 Variable	Description
IWFT	–	Weighting factor type (WFGEN, WFMATG).
IXORZ	–	Wall response factor flag (WFRZ).
KW	–	Weighting factor type (WFMAIN, WFDECN, WFGEN).
LDSTYP	–	Calculation flag.
LENWF	–	Length of wall storage block in AA_i array = 9.
LITEWF	–	Precalculated lighting weighting factors (WFASH).
NDE	–	Number of denominator weighting factors (w_i or p_i) requested (WFMAIN and WFDECN).
NNU	–	Number of numerator weighting factors (v_i or g_i) requested (WFMAIN and WFDECN).
NOPQ	–	Number of opaque walls in space.
NQS	–	Number of terms in the cooling-load sequence QS_i.
NRH	–	Maximum number of hours for which cooling-load sequence is calculated (WFMATG).
NVT_i	–	Actual number of numerator weighting factors determined for weighting-factor type i.
NW	–	Number of walls in space, excluding furniture.
NWALL	–	Number of walls in space, including furniture (WFMATG).
NWI	–	Number of windows in wall (WFDATA).
NWINT	–	Number of windows in space (WFDATA).
NWT_i	–	Actual number of denominator weighting factors determined for weighting-factor type i.

TABLE II.11 (Cont.)

Program Variable	Section II.2.3 Variable	Description
PFA	F_{fa}	Fraction of floor area covered by furniture - see Sec. II.2.3.4.1.
QFLOOR	-	Total solar energy absorbed by floor (WFMATG).
QS_i	Q_i	Cooling-load sequence - see Sec. II.2.3.2.3.
QUN_i	-	Cooling-load sequence from a uniform radiant intensity on all walls (WFMATG).
R1, R1P	$R_1, \dfrac{R_1}{1 + (R_1'/R_1'')^{-1}}$	Parameters used in precalculated weighting factor interpolation (WFASH) - see Sec. II.2.3.5.
RCONC	-	Default convective film resistance on inside wall surface - see DATWF.
RCONF	-	Convective film resistance for furniture - see DATWF.
RFILM	-	Default combined film resistance on inside wall surface - see DATWF.
RHOWT	ρ	Area average of window reflectivity (WFDATA).
RIFR	-	Value input as combined film resistance for delayed wall with INSIDE-FILM-RES keyword.
RINF	R_{in}	Infiltration resistance.
RRADC	-	Radiative film resistance on inside wall surface - see DATWF.
RRADF	-	Radiative film resistance for furniture - see DATWF.
RW	-	Surface to surface thermal resistance of quick wall (WFDATA).
$RZFUR_i$	-	Response factors for furniture - see DATWF.
SOLWF	-	Precalculated solar weighting factors (WFASH).
TR	T_a	Air temperature (WFMATG).

TABLE II.11 (Cont.)

Program Variable	Section II.2.3 Variable	Description
V_{ij}, W_{ij}	–	Final values of weighting factors
V_{1j}	ν_0	j = 1 for solar, j = 3 for people and
V_{2j}	ν_1	equipment, j = 4 for general lighting,
V_{3j}	ν_2	j = 5 for task lighting and j = 6 for
W_{1j}	w_1	conduction.
W_{2j}	w_2	
V_{12}	g_0^*	j = 2 for air temperature.
V_{22}	g_1^*	
V_{32}	g_2^*	
V_{42}	g_3^*	
W_{12}	p_1	
W_{22}	p_2	
W1	w_1	Precalculated weighting-factor term (WFASH).
WCON	–	Window conductance (WFDATA).

3. CURVE FIT
by W. Frederick Buhl

Note: This discussion of CURVE-FIT is presented here in BDL because the CURVE-FIT calculations are actually part of BDL, although the input data will be specified in SYSTEMS and PLANT. The results of the CURVE-FIT calculations are used later in SYSTEMS and PLANT.

Brief Description

In both SYSTEMS and PLANT, the user is given the option of defining equipment performance curves as functions of one or two variables. The definition of these curves is given via the CURVE-FIT instruction in one of two ways: by providing the coefficients of a polynomial or by providing a series of data points. In the latter case, the program performs a least squares fit to the data points with the restriction that the resulting polynomial curve shall pass through the first data point provided by the user.

The program restricts the type of polynomials to the following:

Type	Equation	
LINEAR	$Z = C_1 + C_2X$	(II.114)
QUADRATIC	$Z = C_1 + C_2X + C_3X^2$	(II.115)
CUBIC	$Z = C_1 + C_2X + C_3X^2 + C_4X^3$	(II.116)
BI-LINEAR	$Z = C_1 + C_2X + C_4Y$	(II.117)
BI-QUADRATIC	$Z = C_1 + C_2X + C_3X^2 + C_4Y + C_5Y^2 + C_6XY$	(II.118)

The user either provides the values of C_1, C_2, ..., C_6, or provides a sequence of data points in the form

$$(X_1,Z_1) \; (X_2,Z_2) \; \ldots\ldots\ldots \; (X_n,Z_n)$$

for LINEAR, QUADRATIC or CUBIC equations, or in the form

$$(X_1,Y_1,Z_1) \; (X_2,Y_2,Z_2) \; \ldots\ldots\ldots \; (X_n,Y_n,Z_n)$$

for BI-LINEAR and BI-QUADRATIC equations.

The maximum number of data points that the program will accept is 20 and the minimum depends upon the TYPE of curve:

Type	Minimum Data Points
LINEAR	2
QUADRATIC	3
CUBIC	4
BI-LINEAR	3
BI-QUADRATIC	6

The program is able to fit a curve to a set of points that are not independent, e.g., (0,1) (0,2) do not define a curve of the form $Z = C_1 + C_2X$. In such cases, an error message stating that the points are not independent is printed out in the echo of the input.

Another situation, which gives rise to ambiguity, is not detected by the program and the user is warned in the DOE-2 Reference Manual (Ref. 2) to avoid such sets of data points. This occurs, in the case of BI-QUADRATIC curves, when the independent coordinates (X,Y) of the data points are restricted to lie along two mutually perpendicular straight lines. The reason for the ambiguity, arising from data sets of this sort, can be seen as follows. By a rotation and translation of the X-Y coordinate system, it is possible to transform these data points so that they lie along the transformed X and Y axes. In such a configuration, no information is obtained about the XY term in the bi-quadratic form. In the transformed coordinate system, any coefficient of the XY term will satisfy the data points. When the inverse transformations are performed, the resulting bi-quadratic will generally have arbitrariness in each coefficient.

Detailed Derivation of Curve Fit Algorithm

The algorithm for finding the coefficient of a bi-linear polynomial will be derived in detail, while only the resulting algorithm will be presented for the other curve fits. Their derivation is entirely analagous.

Let the set of data points be (α, β, γ), $(X_1, Y_1, Z_1) \ldots (X_n, Y_n, Z_n)$, where the first data point is distinguished, because the curve (in this case, a surface) must pass through the point α, β, γ.

Let the surface be defined by Eq, (II.117):

$$Z = f(X,Y) = C_1 + C_2X + C_4Y. \qquad \text{(II.119)}$$

It is desired to select C_1, C_2 and C_4 in such a way that the quantity

$$S = \sum_{i=1}^{n} [Z_i - f(X_i,Y_i)]^2 \qquad \text{(II.120)}$$

is a minimum and subject to the restriction

$$f(\alpha,\beta) = \gamma. \tag{II.121}$$

Using the methods of Lagrange multipliers, a variable, λ, is introduced and Eqs. (II.120) and (II.121) are combined to form

$$S'(C_1,C_2,C_4,\lambda) = \sum_{i=1}^{n} [Z_i - f(X_i,Y_i)]^2 - 2\lambda[\gamma - f(\alpha,\beta)] \tag{II.122}$$

where now C_1, C_2, C_4, and λ are considered to be the variables. When they take on their proper values, the factor of λ vanishes and Eq. (II.122) is the same as Eq. (II.120).

Differentiating with respect to C_1, C_2, C_4, and λ in turn, and then setting the results equal to zero, yields the set of equations:

$$\frac{\partial S'}{\partial C_1} = 2\sum_{i=1}^{n} [Z_i - f(X_i,Y_i)]\ (-1) + 2\lambda = 0,$$

$$\frac{\partial S'}{\partial C_2} = 2\sum_{i=1}^{n} [Z_i - f(X_i,Y_i)]\ (-X_i) + 2\lambda\alpha = 0,$$

$$\frac{\partial S'}{\partial C_4} = 2\sum_{i=1}^{n} [Z_i - f(X_i,Y_i)]\ (-Y_i) + 2\lambda\alpha\beta = 0, \text{ and}$$

$$\frac{\partial S'}{\partial \lambda} = -2[\gamma - f(\alpha,\beta)] = 0. \tag{II.123}$$

Substituting for $f(X_i,Y_i)$ from Eq. (II.119) and rearranging terms leads to the following four simultaneous linear equations in C_1, C_2, C_4, and λ:

$$nC_1 + \left(\sum_{i=1}^{n} X_i\right)C_2 + \left(\sum_{i=1}^{n} Y_i\right)C_4 + \lambda = \sum_{i=1}^{n} Z_i$$

$$\left(\sum_{i=1}^{n} X_i\right)C_1 + \left(\sum_{i=1}^{n} X_i^2\right)C_2 + \left(\sum_{i=1}^{n} X_iY_i\right)C_4 + \alpha\lambda = \sum_{i=1}^{n} X_iZ_i$$

$$\left(\sum_{i=1}^{n} Y_i\right)C_1 + \left(\sum_{i=1}^{n} X_iY_i\right)C_2 + \left(\sum_{i=1}^{n} Y_i^2\right)C_4 + \beta\lambda = \sum_{i=1}^{n} Y_iZ_i$$

$$C_1 + \alpha C_2 + \beta C_4 + 0 \cdot \lambda = \gamma. \qquad \text{(II.124)}$$

Using conventional techniques, the coefficients C_1, C_2, and C_4 can be expressed as the ratio of the two determinates:

$$C_j = \frac{A_j}{D}, \text{ for } j = 1, 2, 4, \qquad \text{(II.125)}$$

where the determinant D is given by

$$D = \det \begin{vmatrix} n & \Sigma X & \Sigma Y & 1 \\ \Sigma X & \Sigma X^2 & \Sigma XY & \alpha \\ \Sigma Y & \Sigma Y & \Sigma Y^2 & \beta \\ 1 & \alpha & \beta & 0 \end{vmatrix} \qquad \text{(II.126)}$$

and A_j is derived from D by substituting the column matrix

$$Z = \begin{bmatrix} \Sigma Z \\ \Sigma XY \\ \Sigma YZ \\ \gamma \end{bmatrix} \qquad \text{(II.127)}$$

for the first, second, and third columns of D for j = 1, 2, and 4, respectively. Note that in Eqs. (II.126) and (II.127) the more complex notation of

$$\sum_{i=1}^{n} X_i$$

has been simplified to ΣX, etc.

The corresponding D's and Z's for the other types of curve fits are shown in Table II.12.

TABLE II.12

DETERMINANTS AND COLUMN VECTORS FOR
VARIOUS ORDERS OF CURVE FIT

LINEAR: $$D = \det \begin{vmatrix} n & \Sigma X & 1 \\ \Sigma X & \Sigma X^2 & \alpha \\ 1 & \alpha & 0 \end{vmatrix} ; \quad Z = \begin{bmatrix} \Sigma Z \\ \Sigma XZ \\ \gamma \end{bmatrix}$$

where the first data point is (α,γ).

QUADRATIC: $$D = \det \begin{vmatrix} n & \Sigma X & \Sigma X^2 & 1 \\ \Sigma X & \Sigma X^2 & \Sigma X^3 & \alpha \\ \Sigma X^2 & \Sigma X^3 & \Sigma X^4 & \alpha^2 \\ 1 & \alpha & \alpha^2 & 0 \end{vmatrix} ; \quad Z = \begin{bmatrix} \Sigma Z \\ \Sigma XZ \\ \Sigma X^2 Z \\ \gamma \end{bmatrix}$$

where the first data point is (α,γ).

CUBIC: $$D = \det \begin{vmatrix} n & \Sigma X & \Sigma X^2 & \Sigma X^3 & 1 \\ \Sigma X & \Sigma X^2 & \Sigma X^3 & \Sigma X^4 & \alpha \\ \Sigma X^2 & \Sigma X^3 & \Sigma X^4 & \Sigma X^5 & \alpha^2 \\ \Sigma X^3 & \Sigma X^4 & \Sigma X^5 & \Sigma X^6 & \alpha^3 \\ 1 & \alpha & \alpha^2 & \alpha^3 & 0 \end{vmatrix} ; \quad Z = \begin{bmatrix} \Sigma Z \\ \Sigma XZ \\ \Sigma X^2 Z \\ \Sigma X^3 Z \\ \gamma \end{bmatrix}$$

where the first data point is (α,γ).

BI-QUADRATIC: $$D = \det \begin{vmatrix} n & \Sigma X & \Sigma X^2 & \Sigma Y & \Sigma Y^2 & \Sigma XY & 1 \\ \Sigma X & \Sigma X^2 & \Sigma X^3 & \Sigma XY & \Sigma XY^2 & \Sigma X^2 Y & \alpha \\ \Sigma X^2 & \Sigma X^3 & \Sigma X^4 & \Sigma X^2 Y & \Sigma X^2 Y^2 & \Sigma X^3 Y & \alpha^2 \\ \Sigma Y & \Sigma XY & \Sigma X^2 Y & \Sigma Y^2 & \Sigma Y^3 & \Sigma XY^2 & \beta \\ \Sigma Y^2 & \Sigma XY^2 & \Sigma X^2 Y^2 & \Sigma Y^3 & \Sigma Y^4 & \Sigma XY^3 & \beta^2 \\ \Sigma XY & \Sigma X^2 Y & \Sigma X^3 Y & \Sigma XY^2 & \Sigma XY^3 & \Sigma X^2 Y^2 & \alpha\beta \\ 1 & \alpha & \alpha^2 & \beta & \beta^2 & \alpha\beta & 0 \end{vmatrix} ; \quad Z = \begin{bmatrix} \Sigma Z \\ \Sigma XZ \\ \Sigma X^2 Z \\ \Sigma YZ \\ \Sigma Y^2 Z \\ \Sigma XYZ \\ \gamma \end{bmatrix}$$

where the first data point is (α,β,γ).

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III. LOADS SIMULATOR

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1. LOADS OVERVIEW
by W. Frederick Buhl

1.1 General Comments and Overview

The LOADS program calculates the hourly cooling and heating loads for each space in a building. A cooling load is defined as the rate at which energy must be removed from a space to maintain a constant air temperature in the space. A space is a user-defined subsection of a building. It can correspond to an actual room, or it may be much larger or smaller, depending on the level of detail appropriate for the simulation.

The space cooling (or heating) loads are obtained by a two-step process. First, the space heat gains (or losses) are calculated; then the space cooling loads are obtained from the space heat gains. A space heat gain is defined as the rate at which energy enters and is generated in a space at a given moment.

The space heat gain is divided into various components, depending on the manner in which the energy is transported or generated within the space. The components are:

1. solar heat gain from radiation through windows and skylights,

2. heat conduction gain through walls, roofs, windows, and doors in contact with the outside air,

3. infiltration air,

4. heat conduction gain from walls and floors in contact with the ground,

5. heat conduction through interior walls, floors, ceilings, and partitions,

6. heat gain from occupants,

7. heat gain from lights, and

8. heat gain from equipment.

The calculation of the heat conduction gain through walls involves solving the diffusion equation

$$\frac{\partial^2 T}{\partial x^2} = \frac{1}{\alpha}\frac{\partial T}{\partial t} \tag{III.1}$$

each hour. Of course, if capacitive effects are ignored, the steady state solution can be used. But for many walls, the heat capacity is too large to be ignored. Rather than solving Eq. (III.1) each hour, the equation is presolved for certain simple input or excitation functions; namely, triangular temperature pulses on the inside and outside wall surfaces. This is expressed as

$$q_{inside}(t) = \sum_{i=0}^{\infty} Y_i \, T_{outside}(t-i\Delta) - \sum_{i=0}^{\infty} Z_i \, T_{inside}(t-i\Delta). \qquad \text{(III.2)}$$

Here, Y_i and Z_i are response factors, q_{inside} is the heat flow at the inside wall surface, $T_{outside}$ and T_{inside} are temperatures at the outside and inside wall surfaces, and Δ is the time step. Because the response factors are fixed for the entire simulation, wall properties cannot be varied. In DOE-2, the combined inside film coefficient is included in the wall definition. Thus, varying inside film coefficients cannot be handled by this model. In DOE-2, the outside surface temperature is obtained by an energy balance at the outside surface involving air temperature, the outside film coefficient, the solar radiation absorbed at the outside surface, the infrared radiation reradiated to the sky, and the heat being conducted into the wall. The inside temperature is set equal to the fixed room air temperature (the inside air film is considered as a "layer" of the wall) set by the user, because LOADS is calculating cooling and heating loads.

The other heat gain components are obtained in a simpler manner. The solar gain calculation starts with the direct and diffuse solar radiation components, which are obtained from measured data or computed from a cloud cover model. The radiation is projected onto the glass surfaces and transmitted, absorbed, and reflected in accordance with the properties of the glass in the window. Maxwell's equations are not solved hourly to obtain the transmission, reflection, and absorption. Instead, the problem is presolved for a finite class of window properties, and the dependence of transmission, absorption, and reflection upon window properties and angle of incidence are parameterized in a group of polynomials. The polynomials are 3rd order in the angle of incidence and the coefficients vary with window type.

Heat flow through interior walls and partitions and through surfaces in contact with the soil is treated as steady state. That is, the capacitive effects of the walls are ignored. This is reasonable for the walls and floors in contact with the ground, because ground temperatures vary slowly compared with the time constant of the walls. Interior walls are often light and the temperature differences across them are usually not large. However, there are obviously cases for which the steady state approximation for interior walls will be invalid.

The internal heat gains from lights, people, and equipment, are basically fixed by the user's input. The user is required to specify the maxima and the hourly schedules for the various internal heat gain components for each space. The program simply keeps track of the hourly values of the components that have been defined in the user's input.

In general, space heat gains are not equal to space cooling loads. An increase of radiant energy in a space does not immediately cause a rise in the space air temperature. The radiation must first be absorbed by the walls, cause a rise in the wall surface temperature, and then (by convective coupling between the wall and the air) cause an air temperature rise. The characteristic amount of time this process will take depends on the wall properties; in particular, the wall's heat capacity and its surface properties. The calculation of cooling loads from heat gains can be accomplished in two ways. The first way is to simultaneously solve the energy balance equations at the inside surface of all the surfaces enclosing the space. This method is fairly time consuming but can handle changing conditions in the space, such as time-varying convective coefficients or nighttime insulation over windows. The second method uses a transfer function to obtain a cooling load component from a heat gain component. This is the technique used in DOE-2. The transfer functions are generated by pulsing a heat gain component, such as solar gain, and using the first method to generate a sequence of cooling loads caused by the pulse. The sequence of cooling loads defines a transfer function. The form of the transfer is an infinite series of decaying exponentials. The series is usually reduced to one or two exponentials. One exponential is equivalent to modeling the transfer function as an R-C circuit with one resistor and one capacitor. Because the input (the heat gain component) and the output (the cooling load component) are time series, the transfer function takes the form of a set of coefficients that multiply the two time series. The coefficients are usually called weighting factors, or room response factors. Because the coefficients are fixed for the period of the simulation, the technique is faster than the energy balance technique, but cannot (in principle) handle changing convective film coefficients or nighttime insulation of windows. In practice, as long as the weighting factors are specific for the space being modeled, the transfer function technique yields results that compare favorably with results given by the energy balance technique or by measurement.

DOE-2 contains two types of weighting factors. The <u>precalculated</u> weighting factors are equivalent to a single exponential, or to a R-C circuit with a single resistance and capacitance. They are not specific to the space being modeled. Instead, the user is forced to guess a room capacitance by use of the FLOOR-WEIGHT keyword. Because it is difficult to guess a reasonable value, use of the precalculated weighting factors is not recommended. Custom weighting factors are specific to the space being modeled. Furthermore, two exponentials rather than one are used in defining the transfer functions. Experience indicates that the custom weighting factors should always be used in preference to the precalculated weighting factors.

Finally, it should be noted that there are different transfer functions for different heat gain components, because each component in general has a different proportion of radiative and convective energy transfer. Components with similar fractions of radiative and convective transfer can use the same transfer function. For infiltration, which has no radiative component, the heat gain is equal to the cooling load.

1.2 LOADS Relationship to the Rest of DOE-2

LOADS is the first in the sequence of simulation programs: LOADS, SYSTEMS, PLANT, and ECONOMICS. Input to the program comes from the language BDL (LDL) via the standard file. This input contains the information about the building and its operation supplied by the user. Another input to LOADS is the hourly weather data from the weather file. Lastly, input may come from a library file, which contains such elements as wall material descriptions, wall response factors, room weighting factors, and schedules. The primary outputs of LOADS are the hourly sensible heating and cooling loads for each space. These are passed to SYSTEMS on the hourly file. In addition, electric load, latent load, and infiltration CFM for each space are passed to SYSTEMS on the hourly file. Peak heating and cooling loads for each space and for the building as a whole are saved in LOADS and passed to SYSTEMS on the design file.

To model his building and its HVAC systems correctly, the user must keep in mind the LOADS-SYSTEMS interface, the weather file, and the fact that LOADS does its calculations at a fixed space temperature. If the user does not size his HVAC equipment by hand, SYSTEMS sizes it for him by using the peak loads passed from LOADS. The peak loads come from the design day weather, or from the weather file itself, if no design days are input by the user. Allowing peaks to be chosen from the weather file will almost always result in unrealistic sizing, particularly if TRY weather is being used. TRY years are selected by eliminating the extreme years. Thus, a TRY year would be an extremely unfortunate choice for use in design calculations. Instead, the user should consult the tables of design weather conditions in the ASHRAE 1977 Handbook of Fundamentals (Ref. 1) and construct at least two (summer and winter) design day inputs. The peaks passed to SYSTEMS will then be those created by the design day weather.

The sizing done in SYSTEMS may still be incorrect, because SYSTEMS is sizing on peak loads, not extraction rates. Ideally, the user should pick his fixed space temperature in LOADS so that it corresponds to the thermostat set point at the time of the peak, and the load will, therefore, be approximately equal to the extraction rate. For versions of DOE-2 in which the space temperature cannot be seasonally varied in the LOADS input, it may be necessary to do several LOADS runs and size the HVAC equipment by hand.

One final difficulty in allowing SYSTEMS to do automatic sizing is that SYSTEMS cannot size a system on the coincident peak of a subset of zones in the building. LOADS passes only the individual space peaks and the building coincident peak, so coincident sizing can only be done for a system that serves the whole building.

1.3 Structure of LOADS

LOADS can be broken down into three main categories:

1. initialization and preprocessing,
2. simulation, and
3. writing summary and peak reports.

The first part involves writing verification reports that summarize the user's input, initializing variables for the start of the simulation, and precalculating as many quantities as possible before the start of the hourly simulation.

The major precalculation performed is to transform all the coordinates to one coordinate system, the building coordinate system (see Sec. III.2.1). In addition, if the user has specified that his windows are set back into the wall, three local shading surfaces are created for each window. Before the simulation is begun, it is necessary to fill the variables and arrays that will be used in the simulation with initial estimates. The time series of past outside surface temperatures for each wall, for instance, is initialized to the first hour's outside dry-bulb temperature. Once the variables are initialized, the program is run for three days on the first day's weather and schedules, to allow the response and weighting factors calculations to stablize.

The structure of the simulation itself consists basically of a system of nested loops. The simulation is done in hourly time steps for each hour of the RUN-PERIOD. Within each hour, the program loops once over each space in the building. For each space, the program loops over each wall in the space. Lastly, for each wall, the program loops over each window and door in the wall. Because there is no system of simultaneous equations to be solved, the process does not have to be done more than once each hour. Calculations for each element composing a space are done once only each hour.

Some calculations are done less frequently than once per hour. The shading calculations (see Sec. III.2.4) are done for one day each month. This is primarily because these calculations are extremely time consuming. The results of the calculations are saved and used for the entire month. Thus, it makes little sense for the user to attempt extremely accurate shading calculations by specifying a large number of shading divisions in his LOADS input, because the calculation has the once-per-month approximation built into it. The solar seasonal variables (declination angle, equation of time, etc.) (see Sec. III.2.3) are calculated once per day. This is more than adequate, because these quantities vary slowly.

Lastly, each day the program determines the day of the week and whether daylight-saving time is in effect. This information is needed so that the program can find the correct hourly schedule values once it is within the hourly loop.

Within the hourly loop, but outside the space loop, the solar direction cosines (see Sec. III.2.3) and the split of solar radiation into direct and diffuse components (see Sec. III.2.3) are calculated. In addition, hourly weather variables are obtained, either from the weather file or from the design day weather calculations.

Within the space loop, but outside the wall loop, the interior heat gains from people, lights, and equipment are calculated from the maxima and schedules (see Sec. III.2.5.1).

Within the wall loop, the direct solar radiation is projected onto each wall (see Sec. III.2.7) and the total radiation per unit area on each wall is obtained. The heat conduction gain for each wall is then calculated (see Sec. III.2.6.1 and see Sec. III.2.6.2).

Within the window loop, the heat conduction gain (see Sec. III.2.6.3) and the solar gain through each window (see Sec. III.2.7) is calculated. Similarly, within the door loop the heat conduction through each door is determined (see Sec. III.2.6.1).

When the wall loop is completed, but still within the space loop, the space heat gain and loss components are operated upon by the weighting factors to produce cooling and heating load components (see Sec. III.2.5.2). These are the primary outputs of LOADS that are then passed to SYSTEMS.

The infiltration calculations are performed in various places, depending on what infiltration method was chosen. If the crack method is being employed, CFM's are calculated within the wall, window, and door loops. If air change or residential methods are used, the calculation is done within the space loop, outside the wall loop.

Because the space temperatures are fixed in LOADS, the heat flowing from one space to another through interior walls is a fixed quantity. It is pre-calculated outside the hourly loop and passed to SYSTEMS on the design file. SYSTEMS adjusts this heat flow according to the actual temperatures in the spaces.

2. DETAILS OF ALGORITHMS

2.1 Coordinate Transformations

This algorithm transforms windows, doors, and exterior walls into the building coordinate system (BCS). Coordinates for each vertex of each surface are calculated, by using the user-specified coordinates of one vertex (origin) and the azimuth and tilt of the surface.

Introduction

The user inputs the location of windows and doors relative to the surface coordinate system. Exterior walls are located and oriented relative to the space coordinate system. This is done to simplify the input. The user does not have to mentally locate each surface in the overall BCS. Instead, he can locate the surface relative to a more local entity, either a wall or a space. Before any calculations are done, all surfaces must be put into the same coordinate system, the BCS. Furthermore, the user has located and oriented his surfaces by giving the coordinates of one corner (called the origin) and the azimuth and tilt of the surface outward pointing normal (SON). Coordinates of the remaining vertices must be calculated and saved.

Brief Description

1. Using the input from the keywords HEIGHT and WIDTH, coordinates for the four vertices of a rectangle are defined (in the surface coodinate system).

2. WINDOWs and DOORs have their vertices defined in the surface coordinate system.

3. The keywords AZIMUTH, TILT, X, Y, and Z in the EXTERIOR-WALL instruction are used to calculate coordinates of each vertex relative to the space coordinate system.

4. EXTERIOR-WALLs, DOORs, and WINDOWs are then transformed from the space coordinate system to the BCS.

5. New azimuths and tilts, for each EXTERIOR-WALL, DOOR, and WINDOW, are calculated relative to the BCS.

Details and Derivation

Step 1. Locating the vertices of a rectangular surface in the surface coordinate system.

The first step is tc use the HEIGHT and WIDTH input to assign the coordinates of each vertex of a rectangular surface.

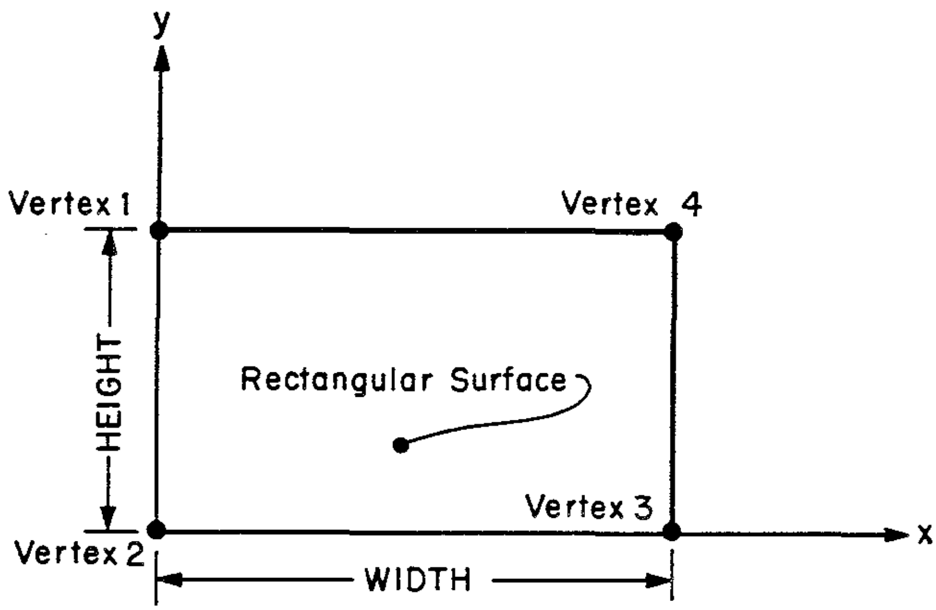


Fig. III.1. Locating the vertices of a rectangular surface in the surface coordinate system.

Vertex 1	Vertex 3
x(1) = 0	x(3) = WIDTH
y(1) = HEIGHT	y(3) = 0
z(1) = 0	z(3) = 0

Vertex 2	Vertex 4
x(2) = 0	x(4) = WIDTH
y(2) = 0	y(4) = HEIGHT
z(2) = 0	z(4) = 0

where x(i) is the x coordinate of the ith vertex, etc.

Notice that the vertices are numbered counterclockwise. Be definition, the number 2 vertex (lower left-hand corner when looking back down the surface outward pointing normal) is at the origin. It is this vertex that the user locates when he specifies values for the X, Y, and Z keywords in the EXTERIOR-WALL, WINDOW, and DOOR instructions. Step 1 is performed for building shades, in addition to windows, doors, and exterior walls (see BUILDING-SHADE instruction).

Step 2. Locating WINDOWs and DOORs on an EXTERIOR-WALL.

Windows and doors are now transformed to the surface coordinate system. That is, their vertices are located relative to the lower left-hand corner (origin) of the exterior wall they are in.

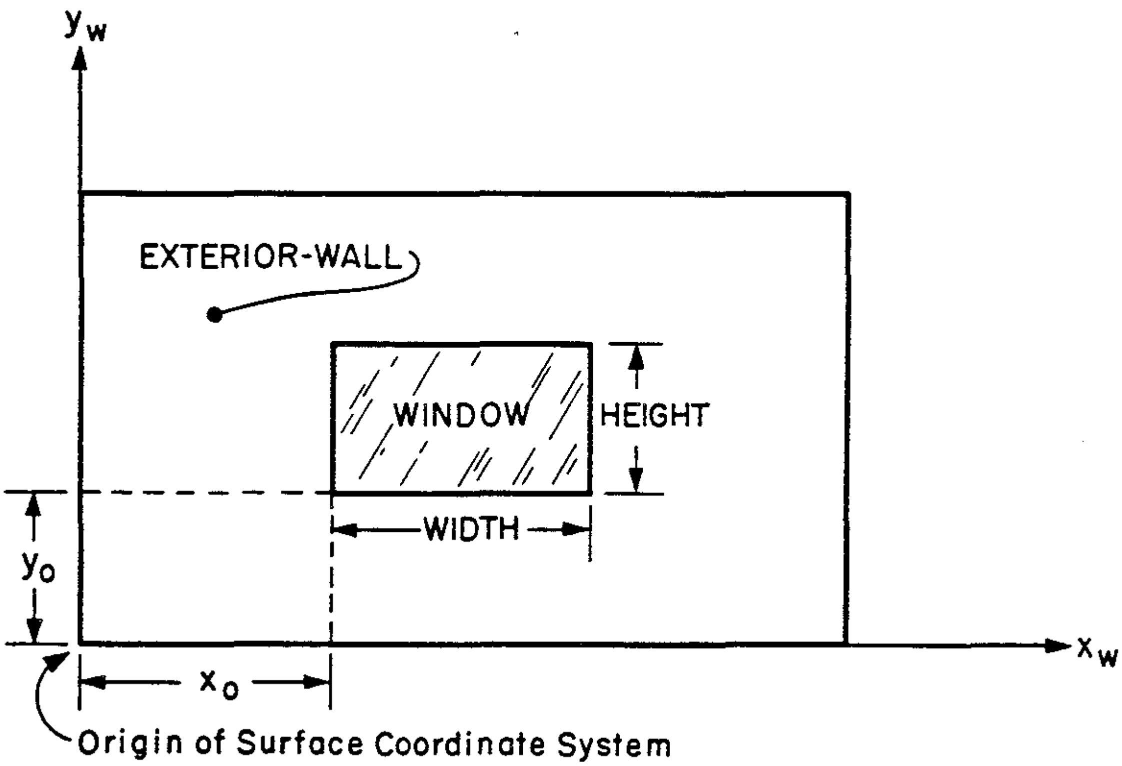


Fig. III.2. Locating WINDOWs and DOORs on an EXTERIOR-WALL.

If the coordinates of the vertices of the WINDOW, <u>before</u> it is located on the EXTERIOR-WALL, can be expressed as

$$x(1),\ x(2),\ \ldots,\ x(i)$$
$$y(1),\ y(2),\ \ldots,\ y(i)$$
$$z(1),\ z(2),\ \ldots,\ z(i)$$

and the coordinates of the vertices of the WINDOW, <u>after</u> it is located on the EXTERIOR-WALL, can be expressed as

$$x_w(1),\ x_w(2),\ \ldots,\ x_w(i)$$
$$y_w(1),\ y_w(2),\ \ldots,\ y_w(i)$$
$$z_w(1),\ z_w(2),\ \ldots,\ z_w(i)$$

then,

$x_w(i) = x(i) + x_o$,
$y_w(i) = y(i) + y_o$,
$z_w(i) = 0$, and
$i = 1$, number of vertices.

Step 3. Calculation of the coordinates of the vertices of EXTERIOR-WALLs, WINDOWs, and DOORs in the space coordinate system.

Exterior walls, doors, and windows now have their vertices located relative to the surface coordinate system; that is, a coordinate system with its origin at the second vertex of an exterior wall and the x axis running from the second to the third vertex; the wall lies in the x_w y_w plane. The AZIMUTH and TILT keywords, input through the EXTERIOR-WALL instruction, must now be used to give the wall its correct orientation. Also, the X, Y, and Z keywords in the EXTERIOR-WALL instruction must be used to locate the second vertex of the exterior wall, relative to the origin of the space coordinate system. First, apply TILT and AZIMUTH.

From Fig. III.3, we see that

$$x_s(i) = x_w(i)\cos(\phi) + y_w(i)\sin(\phi)\cos(\mathrm{TILT}),$$

$$y_s(i) = -x_w(i)\sin(\phi) + y_w(i)\cos(\phi)\cos(\mathrm{TILT}), \text{ and}$$

$$z_s(i) = z_w(i)\sin(\mathrm{TILT}).$$

These formulas are good for all the vertices. Because AZIMUTH = ϕ + 180 and

$$\cos(\phi + 180) = -\cos(\phi)$$

$$\sin(\phi + 180) = -\sin(\phi),$$

when the offsets from the space coordinate system origin to the surface origin are added in,

$$x_s(i) = x_0 - x_w(i)\cos(\mathrm{AZIMUTH}) - y_w(i)\sin(\mathrm{AZIMUTH})\cos(\mathrm{TILT}),$$

$$y_s(i) = y_0 + x_w(i)\sin(\mathrm{AZIMUTH}) - y_w(i)\cos(\mathrm{AZIMUTH})\cos(\mathrm{TILT}), \text{ and}$$

$$z_s(i) = z_0 + y_w(i)\sin(\mathrm{TILT}) \qquad \text{(III.3)}$$

where x_0, y_0, and z_0 are the X, Y, and Z keyword values input through the EXTERIOR-WALL instruction.

The transformation, defined in Eq. (III.3), has one noticeable peculiarity: if AZIMUTH = TILT = x_0 = y_0 = z_0 = 0, we see that

$$x_s(i) = -x_w(i), \text{ and}$$

$$y_s(i) = -y_w(i).$$

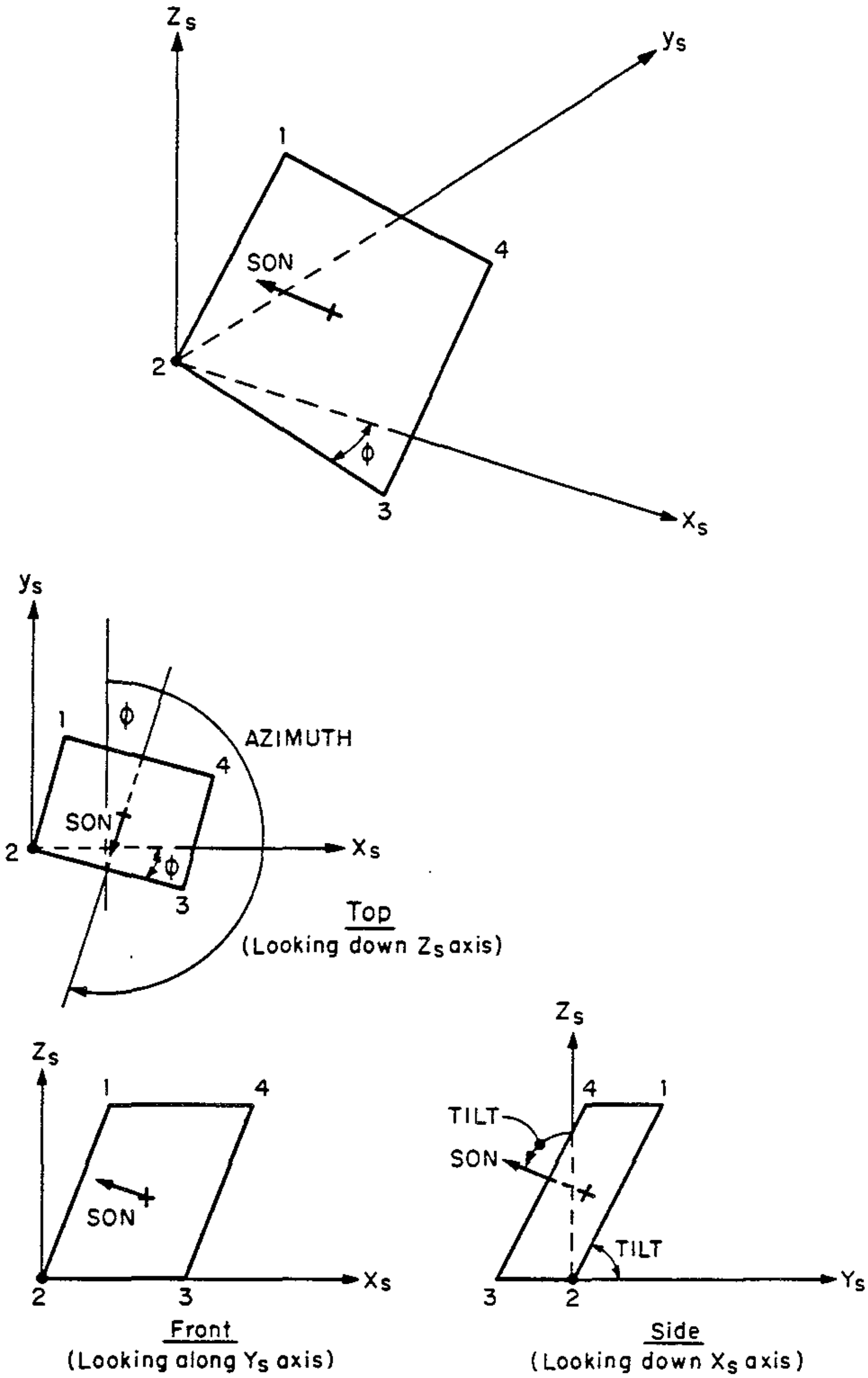


Fig. III.3. Calculating the coordinates of the vertices of EXTERIOR-WALLs, WINDOWs, and DOORs in the space coordinate system.

This results from the fact that AZIMUTH has been defined as the angle between the y axis and the projection of the surface outward normal (SON) on the x_s y_s plane, instead of making AZIMUTH = ϕ, the amount the surface has actually been rotated about the z_s axis.

Since AZIMUTH = ϕ + 180, a way to mentally orient a wall, given its AZIMUTH and TILT, is to rotate it by the amount of TILT upwards about the x_w axis, then to rotate it 180° about the z_s axis, followed by a further rotation of ϕ about the z_s axis.

Step 3 is also used to locate and orient the building shades. Because the input for the BUILDING-SHADE instruction is relative to the BCS, at the end of step 3, the building shades are already located and oriented correctly in the BCS. Step 4 is, therefore, not performed for building shades.

Step 4. Transforming EXTERIOR-WALLs, DOORs, and WINDOWs from the space coordinate system to the building coordinate system.

The exterior walls, doors, and windows have now been located relative to the space coordinate system. They must now be transformed to the BCS. This involves a rotation about the z_s axis and a translation, so

$$x_b(i) = x_o + x_s(i)\cos(\text{AZIMUTH}) - y_s(i)\sin(\text{AZIMUTH}),$$

$$y_b(i) = y_o - x_s(i)\sin(\text{AZIMUTH}) - y_s(i)\cos(\text{AZIMUTH}), \text{ and}$$

$$z_b(i) = z_o + z_s(i),$$

where x_o, y_o, and z_o are the quantities input for the X, Y, and Z keywords in the SPACE instruction, and AZIMUTH is the quantity input for the AZIMUTH keyword in the SPACE instruction.

Step 5. Calculating new azimuths and tilts for EXTERIOR-WALLs, DOORs, and WINDOWs relative to the building coordinate system.

An area vector for each polygon is calculated. The magnitude of the area vector is actually already known, because the area was needed in the weighting-factor calculations. The direction of the area vector (the direction of the surface outward normal) is needed to calculate a new azimuth and tilt of the surface in the BCS. These two angles are used in calculating how much sunlight falls on each surface.

Let O' be a point in the plane of the polygon (and totally enclosed by it) (see Fig. III.4). V represents a vertex of the polygon. O is the origin of the BCS. Then the area of the polygon is given by the sum of the area of the triangles V_{i+1} O' V_i.

This area of each triangle is 1/2 base x height or, in vector terms

$$\vec{A}_i = 1/2\ \overrightarrow{O'V}_{i+1} \times \overrightarrow{O'V}_i$$

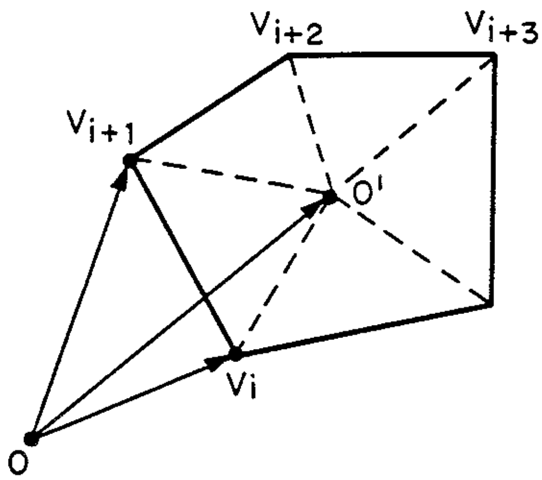


Fig. III.4. Calculating the area vector.

now

$$\vec{O'V_i} = \vec{OV_i} - \vec{OO'}$$

so

$$\vec{A_i} = (\vec{OV_{i+1}} - \vec{OO'}) \times (\vec{OV_i} - \vec{OO'}) = \vec{OV_{i+1}} \times \vec{OV_i} + \vec{OO'} \times (\vec{OV_{i+1}} - \vec{OV_i}).$$

But $\vec{OV_{i+1}} - \vec{OV_i}$ is a vector running along the edge of the polygon from vertex i to vertex i+1. When summed over all edges, this will be zero (i.e., the polygon is closed). Thus

$$\vec{A} = \sum_{i=1}^{n} A_i = 1/2 \sum_{i=1}^{n} \vec{OV_{i+1}} \times \vec{OV_i}.$$

The components of A are

$$XCOMP = 1/2 \sum_{i=1}^{n} (y_i\, z_j - y_j\, z_i),$$

$$YCOMP = 1/2 \sum_{i=1}^{n} (z_i\ x_j - z_j\ x_i), \text{ and}$$

$$ZCOMP = 1/2 \sum_{i=1}^{n} (x_i\ y_j - x_j\ y_i),$$

where

$j = i + 1$ for $i < n$,

$j = 1$ for $i = n$, and

n = the number of vertices.

The tilt of the surface in the BCS is the arc cosine of the z-direction cosine of the area vector, so

$$TILT = \cos^{-1}(ZCOMP)/|\vec{A}|).$$

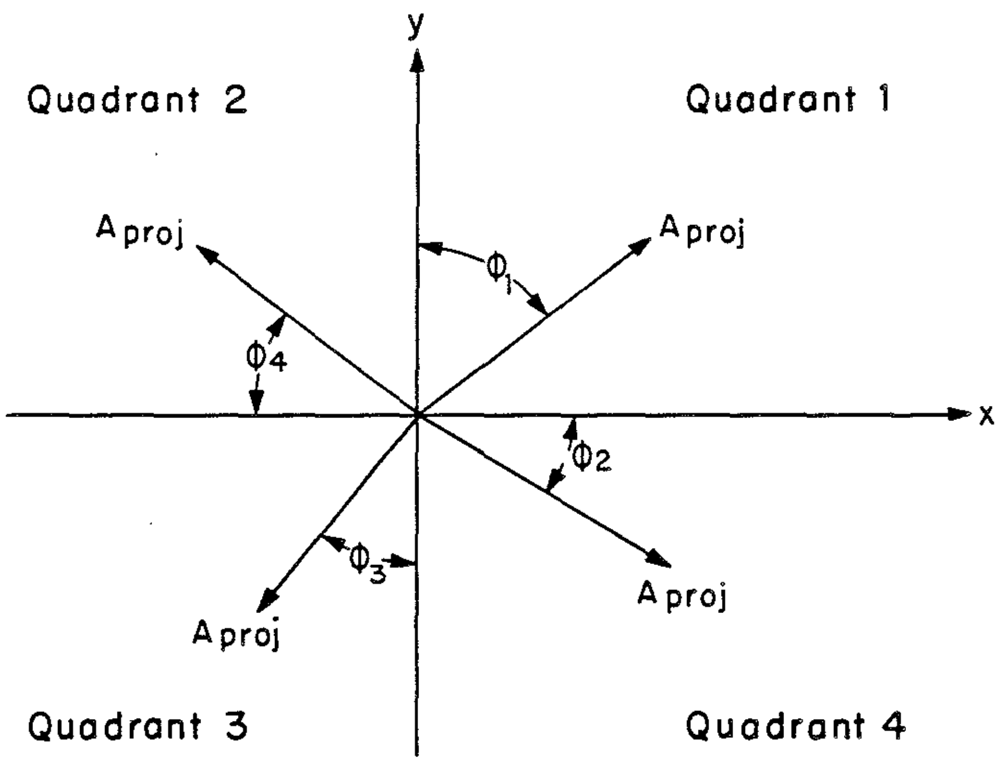


Fig. III.5. Determining the azimuth of the area vector.

If we project $\vec{A}$ onto the x-y plane, the azimuth of the surface in the BCS can be found from the projected vector $\vec{A}_{proj}$.

$$\left|\vec{A}_{proj}\right| = \sqrt{(XCOMP)^2 + (YCOMP)^2}\ .$$

If $\left|\vec{A}_{proj}\right|$ is small ("less than" $10^{-4} * |\vec{A}|$), AZIMUTH = 0°.

If $\vec{A}_{proj}$ is in quadrant 1, AZIMUTH $= \phi = \sin^{-1}[XCOMP/|\vec{A}_{proj}|]$.

If $\vec{A}_{proj}$ is in quadrant 2, AZIMUTH $= 270^\circ + \phi_4 = 3\pi/2 + \sin^{-1}[YCOMP/|\vec{A}_{proj}|]$.

If $\vec{A}_{proj}$ is in quadrant 3, AZIMUTH $= 180^\circ + \phi_3 = \pi + \sin^{-1}[XCOMP/|\vec{A}_{proj}|]$.

If $\vec{A}_{proj}$ is in quadrant 4, AZIMUTH $= 90^\circ + \phi_2 + \pi/2 + \sin^{-1}[YCOMP/|\vec{A}_{proj}|]$.

Breakdown by Subroutine

Step 1 is done in subroutine RECTAN.
Step 2 is done in subroutine TRANSL.
Step 3 is done in subroutine WALLOC.
Step 4 is done in subroutine ZONLOC.
Step 5 is done in subroutine APOL.

2.2 Weather

2.2.1 Weather Variables

To perform its hourly simulation, DOE-2 needs hourly weather information. It obtains this information from a packed binary weather file named WEATHER. We will describe the weather variables used by the program and say a little about how they were obtained.

The variables are

WBT — The outdoor wet-bulb temperature in °F. This is hourly report variable GLOBAL(3).

DBT — The outdoor dry-bulb temperature in °F. This is hourly report variable GLOBAL(4).

PATM — The atmospheric pressure in inches of Hg. This is hourly report variable GLOBAL(5).

CLDAMT — The cloud amount in tenths (1-10). This is hourly report variable GLOBAL(6).

IWNDDR — The wind direction in 16ths of a circle (0-15). 0 is north; the numbers increase in a clockwise direction. This is hourly report variable GLOBAL(9).

HUMRAT — The outdoor humidity ratio in lbs H_2O/lbs of dry air. This is hourly report variable GLOBAL(10).

DENSTY — The density of outdoor air in lbs/ft^3. This is hourly report variable GLOBAL(11).

ENTHAL — The specific enthalpy of the outdoor air in Btu/lb. This is hourly report variable GLOBAL(17).

SOLRAD — The total horizontal solar radiation in Btu/ft^2. This is hourly report variable GLOBAL(13).

DIRSOL — The direct normal solar radiation in Btu/ft^2. This is hourly report variable GLOBAL(14).

ICLDTY — The cloud type (0, 1, or 2). Cloud type 0 stands for cirrus clouds, the most transparent cloud cover. Cloud type 1 means stratus and is given the most opaque cloud cover modifier. Cloud type 2 represents a condition intermediate between 0 and 1 and is the default cloud type. This is hourly report variable GLOBAL(15).

WNDSPD — The wind speed in knots. This is hourly report variable GLOBAL(16).

HUMRAT, DENSTY, and ENTHAL are primarily used in the SYSTEMS subprogram.

There are two types of weather files: solar and normal. Solar files contain solar radiation data as described above under SOLRAD and DIRSOL. Normal files contain no solar radiation information. SOLRAD and DIRSOL will always be zero. Solar radiation is calculated in LOADS from the cloud cover and cloud type information. The variables RDNCC and BSCC [GLOBAL(21) and GLOBAL(22)] contain the result of the calculation.

Because the weather variables are packed, i.e., converted to positive integers and stored with more than one quantity per word, a decision has been made on how much precision to keep for each variable. The precisions are

WBT	nearest whole °F,
DBT	nearest whole °F,
PATM	nearest tenth of an inch in Hg,
CLDAMT	nearest integer,
HUMRAT	nearest .0001,
DENSTY	nearest .001, and
ENTHAL	nearest .5

The weather data is derived from weather tapes supplied by the National Climatic Center. The variables DBT, WBT, PATM, CLDAMT, WNDSPD, ICLTY, and IWNDDR are directly derived from data on the tapes. When information is missing for one or more hours, DBT, WBT, PATM, CLDAMT, and WNDSPD are linearly interpolated from the previously available value to the next available value. IWNDDR and ICLDTY are assigned the previous available value. WBT is always forced to be less than or equal to DBT. The other variables are calculated from the formulas

$$\text{HUMRAT} = .622\,\frac{\text{PPWV}}{(\text{PATM} - \text{PPWV})}\,, \tag{III.4}$$

$$\text{DENSTY} = 1/[.754(\text{DBT} + 459.7)(1 + 1.606*\text{HUMRAT})]/\text{PATM}, \text{ and} \tag{III.5}$$

$$\text{ENTHAL} = .24\text{DBT} + (1061 + .444\text{DBT})\text{HUMRAT}, \tag{III.6}$$

where

PPWV = the partial pressure of water vapor (in Hg),

.662 = the ratio of the molecular weight of water vapor (18.01534) to the molecular weight of dry air (28.9645),

1.606 = the reciprocal of the ratio .622,

.754 = the factor for converting air and water partial pressure into inches of mercury (ft^2-in/lb-°R)

459.7 = the factor to convert DBT to absolute temperature,

.24 = the specific heat of air (Btu/lb-°F), 1061 = the enthalpy of saturated water vapor at 0°F (Btu/lb), and

.444 = the specific heat of water vapor (Btu/lb-°F).

These equations are derived on pages 5.3 and 5.4 of Ref. 1. PPWV is calculated by the Goff formulas as shown on page 5.2 of Ref. 1.

No correction to any of the weather variables is made to allow for differing conditions at the weather station and at the location of the building being simulated. The weather variables used by the program are the variables measured at the weather stations.

Some weather tapes (TMY, SOLMET) contain measured solar radiation data. These tapes can be used to produce the solar type DOE-2 weather files. Missing radiation data is filled in by linear interpolation, in the same manner as for DBT, WBT and the other variables.

2.2.2 Design Day Weather

The design day feature enables the user to define his own weather conditions. From the user's input, hourly weather for one day is created. The program then runs repetitively on this weather for as long as the user has specified in his run period. Peak loads generated by the design day weather are passed to SYSTEMS for use in the design calculations. Thus, the design day feature is most useful for sizing the HVAC system based on design weather conditions more extreme than those on the weather file.

Dry-bulb and Dewpoint

The user inputs the maximum and minimum dry-bulb temperature for the day (T_h and T_l), along with the hour of the high and low (t_h and t_l) through the keywords DRYBULB-HI, DRYBULB-LO, HOUR-HI, and HOUR-LO in the DESIGN-DAY instruction. The program creates a daily temperature cycle from two cosine curves with a peak of T_h at t_h and a low of T_l at t_l.

If the low occurs before the high ($t_l < t_h$), then:

$$T_{av} = \frac{T_h + T_l}{2},$$

$$T_\Delta = \frac{T_h - T_l}{2},$$

$$DBT = T_{av} - T_\Delta * \cos\left\{\left[\frac{\pi}{(t_h - t_l)}\right] (t - t_l)\right\}, \text{ if } t_l < t \leq t_h,$$

$$DBT = T_{av} + T_{\Delta} * \cos\left\{\left[\frac{\pi}{24 - (t_h - t_1)}\right](t - t_h)\right\}, \text{ if } t > t_h, \text{ and}$$

$$DBT = T_{av} + T_{\Delta} * \cos\left\{\left[\frac{\pi}{24 - (t_h - t_1)}\right](t - t_h + 24)\right\}, t \leq t_1.$$

where t is the present hour. The situation is illustrated by Fig. III.6.

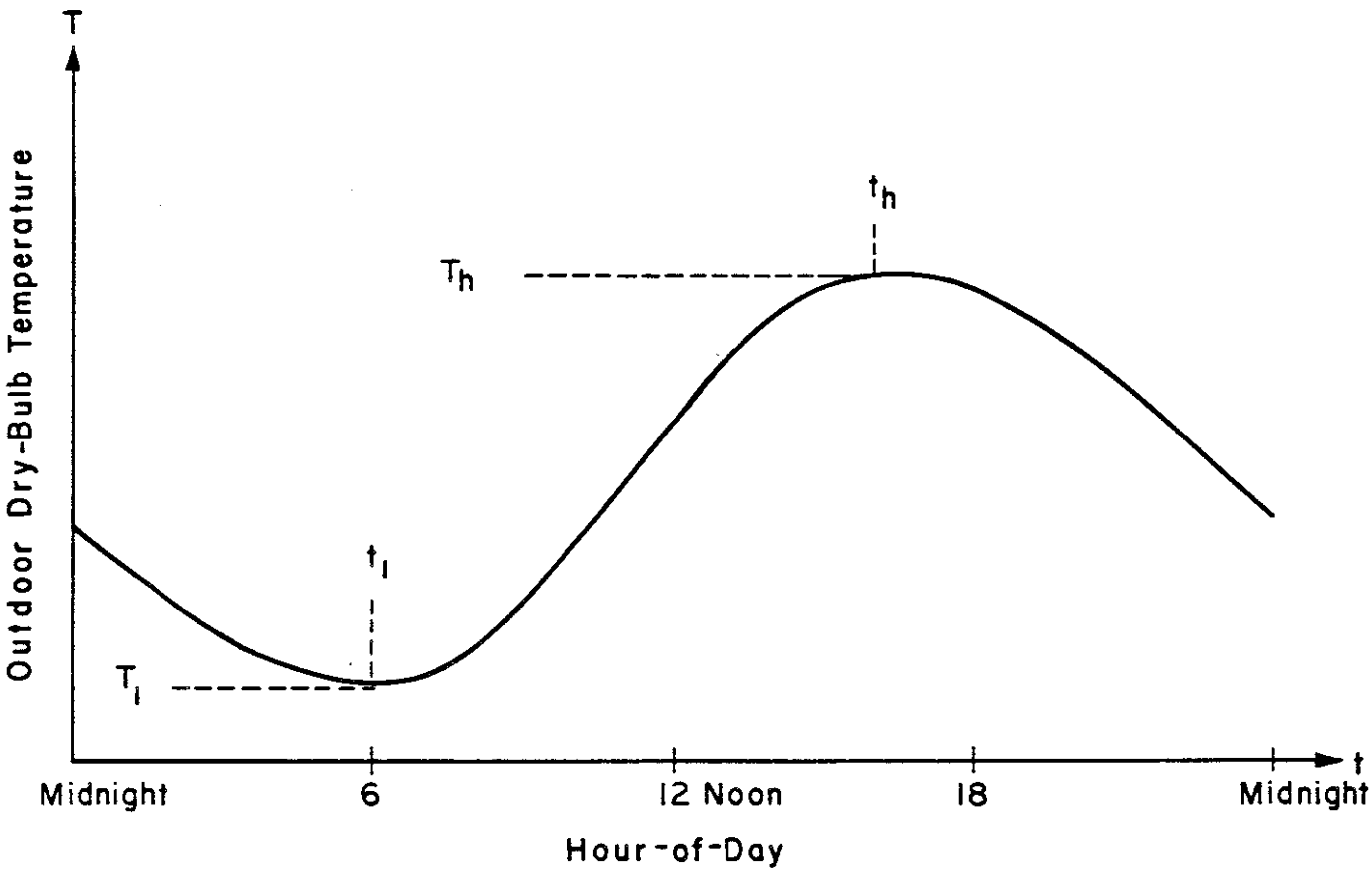


Fig. III.6. Creating a daily temperature profile from two known temperatures (and times).

For $t_1 \geq t_h$:

$$DBT = T_{av} + T_{\Delta}\cos\left\{\left[\frac{\pi}{t_1 - t_h}\right](t - t_h)\right\}, t_h < t \leq t_1,$$

$$DBT = T_{av} - T_{\Delta}\cos\left\{\left[\frac{\pi}{24 - (t_l - t_h)}\right](t - t_l)\right\},\ t > t_l, \text{ and}$$

$$DBT = T_{av} - T_{\Delta}\cos\left\{\left[\frac{\pi}{24 - (t_l - t_h)}\right](t - t_l + 24)\right\},\ t \leq t_l.$$

The exact same procedure is used to generate a daily cycle for dewpoint temperature from the user's input DEWPT-HI, DEWPT-LO, DHOUR-HI, and DHOUR-LO.

All other variables are held constant at the values input by the user. The user can generate a constant dry-bulb or dewpoint cycle by inputting equal values for DRYBULB-HI and DRYBULB-LO on DEWPT-HI and DEWPT-LO.

The humidity ratio and enthalpy are calculated by Eqs. (III.4) and (III.5) of the previous section. The vapor pressure is the saturated vapor pressure at the dewpoint, again calculated by the Goff formula (Ref. 1, pg 5.2). The pressure used is the design pressure,

PATMDS = 29.92E(-.0000368 * BALTIT),

where BALTIT is the altitude input by the ALTITUDE keyword in the BUILDING-LOCATION command. The user must beware of inputting data that will generate relative humidities greater than 100 per cent. No checks are made for this condition in the design day algorithm.

Finally, the hourly wet-bulb temperature is calculated from the enthalpy and PATMDS using the procedure given on pages 5.4 and 5.5 of Ref. 1. The explicit algorithm is given on page 103, Ref. 2.

2.3. Solar Calculations

This section shows how the program calculates the direct normal solar radiation (that is, beam radiation on a surface perpendicular to the incoming radiation) and the diffuse horizontal solar radiation (that is, diffuse radiation from the sky on a horizontal surface) on a cloudy day.

Brief Description

1. The following solar seasonal quantities are used in the calculation:

tan(DECLN)	- tangent of the declination angle
EQTIME	- solar equation of time
SOLCON	- solar constant
ATMEXT	- atmospheric extinction coefficient
SKYDFF	- sky diffuse factors.

    Because these quantities vary slowly throughout the year, they are calculated once per day. They are calculated as a truncated Fourier series in the variable $(2\pi/366)$IDOY; i.e., the day of year converted to an angle.

    At the same time that the above quantities are obtained, the hour angle of sunrise (GUNDOG), Fig. III.7, is calculated from the latitude (STALAT) and the declination angle (DECLN):

    $$\text{GUNDOG} = \cos^{-1}\,[-\tan(\text{STALAT}) * \tan(\text{DECLN})]. \tag{III.7}$$

2. For each hour of the day, the solar direction cosines are then calculated.

    First, the hour angle (HORANG) is obtained in radians:

    $$\text{HORANG} = .2618\ (\text{IHR}-12 + \text{ITIMZ} + \text{EQTIME} - 1/2) - \text{STALON}, \tag{III.8}$$

    where .2618 converts hours to radians

    $$\left(\frac{2\pi \text{ radians}}{24 \text{ hr}}\right),$$

    IHR is the hour of the day (corrected for daylight saving, if necessary), ITIMZ is the time zone, EQTIME is the solar equation of time, and STALON is the longitude. Note that the hour angle is calculated at the middle of the time interval (IHR-1, IHR), that is, at the half-hour point.

3. A check is made to determine if the sun is down for the entire hourly interval (IHR-1, IHR). The variable TEST is defined to be the hour angle of the interval boundary nearest noon:

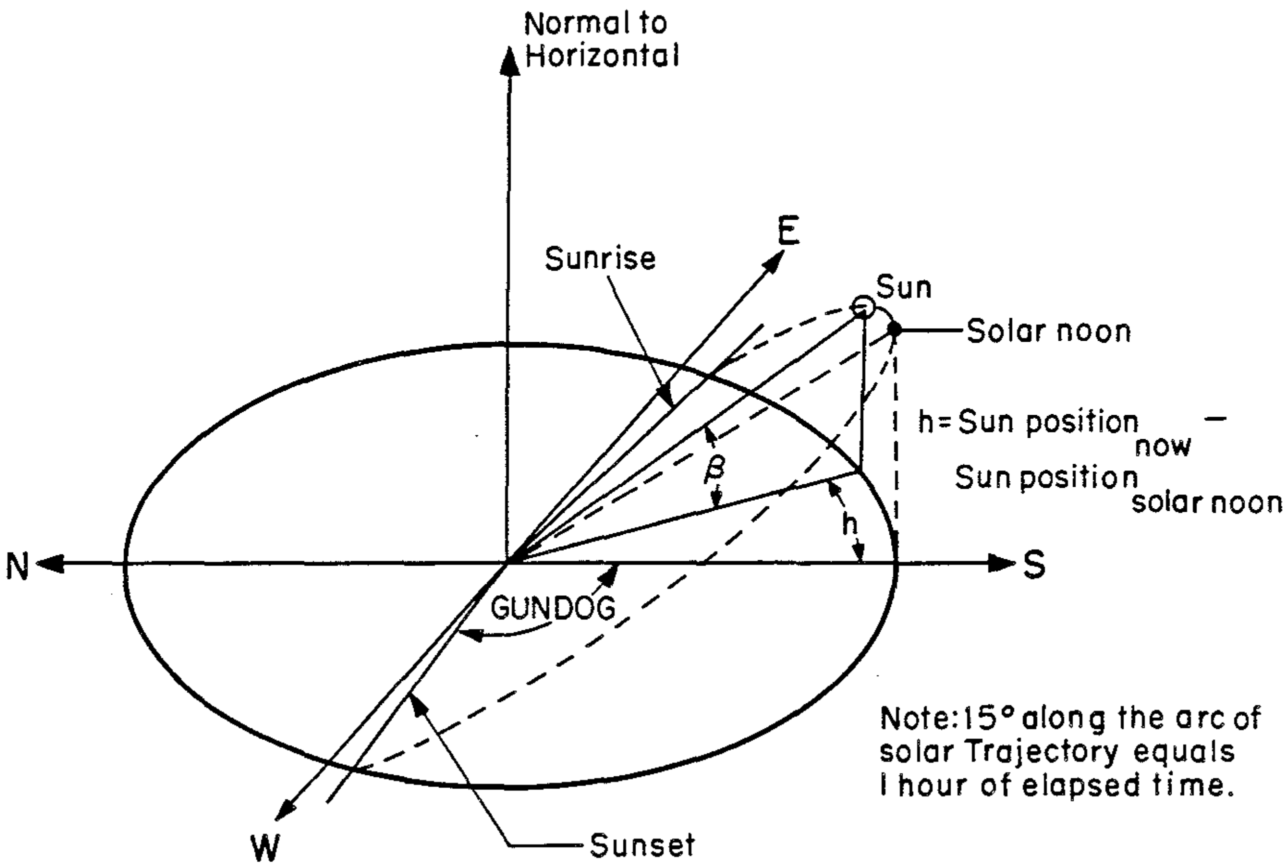


Fig. III.7. Diurnal solar geometry.

h = hour angle; h = 0 at solar noon (radians).
β = solar altitude angle; β = 0 at sunrise and sunset (radians).
GUNDOG = hour angle at sunrise and sunset; β = 0 (radians).

if IHR < 12, TEST = HORANG + .1309 and

if IHR $\geq$ 12, TEST = HORANG - .1309

where

$$.1309 = \frac{2\ \pi\ \text{radians/day}}{48\ \text{half hours/day}},$$

which converts the hour angle to radians.

If $|\text{TEST}| > |\text{GUNDOG}|$, the sun is down for the entire hour, and the calculations of solar direction cosines and solar direct and diffuse radiation are omitted because they are not needed.

4. Next, a check is made to determine if sunrise or sunset occurred in the present hourly interval

$$\text{DIFF} = |\text{GUNDOG}| - |\text{TEST}|.$$

If $0 \geq \text{DIFF} < .2618$, the sun rose or set in the present hourly interval ($\text{IHR}-\bar{1}$, IHR). The constant

$$.2618 = \frac{2\ \pi \text{ radians/day}}{24 \text{ hours/day}} .$$

The hour angle is then reset to be the hour angle halfway between sunrise or sunset and the interval boundary nearest noon:

$$\text{for IHR} < 12,\ \text{HORANG}_{new} = \text{HORANG}_{old} + 1/2(.2618 - \text{DIFF}) \text{ and}$$

$$\text{for IHR} \geq 12,\ \text{HORANG}_{new} = \text{HORANG}_{old} - 1/2(.2618 - \text{DIFF}).$$

Finally, FSUNUP, the fraction of the hour that the sun is above the horizon, is obtained

$$\text{FSUNUP} = 3.8197 * \text{DIFF}.$$

The constant

$$3.8197 = \frac{24 \text{ hours}}{2\ \pi \text{ radians}} .$$

If the sun is up for the entire hour, FSUNUP = 1.

5. The solar direction cosines [RAYCOS(1), RAYCOS(2), and RAYCOS(3)] are given by the formulas:

$$\begin{aligned}\text{RAYCOS}(1) = {} & [\cos(\text{HORANG}) \cos(\text{DECLN}) \sin(\text{STALAT}) \\ & - \sin(\text{DECLN}) \cos(\text{STALAT})] \sin(\text{BAZIM}) \\ & - \sin(\text{HORANG}) \cos(\text{DECLN}) \cos(\text{BAZIM}),\end{aligned}$$

$$RAYCOS(2) = [\cos(HORANG)\cos(DECLN)\sin(STALAT) - \sin(DECLN)\cos(STALAT)]\cos(BAZIM) - \sin(HORANG)\cos(DECLN)\sin(BAZIM), \text{ and}$$

$$RAYCOS(3) = \sin(STALAT)\sin(DECLN) + \cos(STALAT)\cos(HORANG)\cos(DECLN), \tag{III.9}$$

where BAZIM equals the building azimuth angle, measured from true north to the building Y-axis.

6. Next, if solar data are not on the weather file, direct normal solar radiation (RDN) and diffuse solar radiation (BSUN) are obtained for clear sky conditions as

$$RDN = SOLCON * CLRNES * e^{-ATMEXT/RAYCOS(3)} \tag{III.10}$$

and

$$BSUN = (SKYDFF/CLRNES^2)RDN, \tag{III.11}$$

where SOLCON is a fitted solar constant, CLRNES is the clearness number for the hour, ATMEXT is the solar extinction coefficient, and SKYDFF is the sky diffuse factor.

7. For cloudy conditions, the cloud cover factor (CLDCOV) is then calculated. This factor is simply the total solar radiation on a horizontal surface for cloudy conditions (SOLRAD) divided by the total solar radiation on a horizontal surface for clear conditions. It is obtained from empirical formulae that are third order polynomials in the cloud cover.

8. Last, the direct normal and diffuse solar radiation for cloudy conditions are calculated. The total horizontal solar radiation for cloudy conditions is

$$SOLRAD = [RDN * RAYCOS(3) + BSUN]\ CLDCOV * FSUNUP. \tag{III.12}$$

The direct normal radiation for cloudy conditions is

$$RDNCC = RDN\ (1 - CLDAMT/10) * FSUNUP. \tag{III.13}$$

The diffuse radiation for cloudy conditions is

$$BSCC = SOLRAD - [RDNCC * RAYCOS(3)].$$

If BSCC < 0, it is set equal to zero.

Details and Derivation

Step 1

The solar quantities that vary seasonally must first be defined in detail. The solar declination angle is the angle between the earth-sun line and the equatorial plane. Because the earth is tilted a maximum of 23.5°, the declination angle varies from +23.5° in the summer (June) to -23.5° in the winter (December).

The earth's orbit around the sun is an ellipse. This means that the orbital velocity varies with the time of the year. The result is a difference between apparent solar time (sun dial time) and the time given by a clock running at constant speed. The equation of time (EQTIME) is the seasonally varying correction term that allows the calculation of apparent solar time from local clock time (see Fig. III.8).

Solar equation of time takes into account the various perturbations in the earth's orbit and rate of rotation that affect the time the sun appears to cross the observer's meridian.

The solar constant (SOLCON) is the intensity of solar radiation on a surface normal to the sun's rays at the top of the atmosphere. Because the earth-sun distance varies seasonally, this number must also vary. The solar constant varies from a minimum of 416 Btu/ft^2-hr to a maximum of 444 Btu/ft^2-hr. The solar constant used in this algorithm is not the actual physical solar constant, but rather [combined with the atmospheric extinction coefficient in Eq. (III.10), the result of a fit to measured solar data (Refs. 3 and 4). The solar constant used here is always smaller than the true solar constant. It represents average clear sky conditions. On a very clear day, direct normal values may be as much as 15 percent higher than given from Eq. (III.10 with CLRNES = 1.

The atmospheric extinction coefficient (ATMEXT) corrects for the attenuation of the solar energy by the atmosphere. It varies seasonally because of the varying amounts of dust and water vapor in the atmosphere. Values for this variable were obtained in conjunction with SOLCON by a fit of Eq. (III.10) to measured solar data (Refs. 3 and 4). This constant cannot be directly related to the physical atmospheric transmittivity.

The sky diffuse factor (SKYDFF) is an ad hoc factor used to obtain diffuse radiation from the direct normal solar radiation. It was obtained by a fit of Eq. (III.11) with CLRNES = 1 to measured solar data (Refs. 3 and 4).

Monthly values of the five seasonal solar quantities are tabulated in Table III.1 (Ref. 1). Values are for the 21st day of each month.

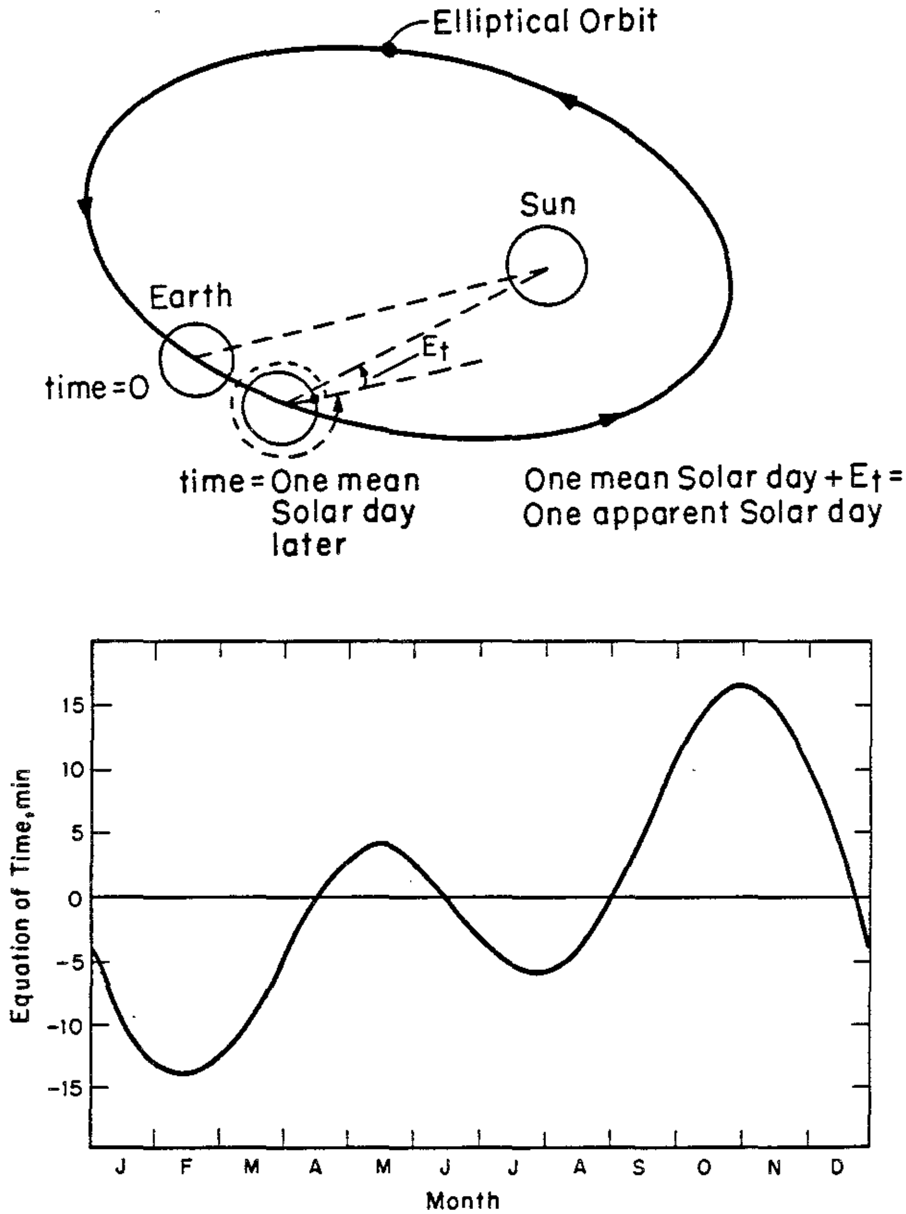


Fig. III.8. Solar equation of time.

For convenient use in a computer program, the five quantities have been parameterized as functions of the day of year. The functional form is a truncated Fourier series.

TABLE III.1

SOLAR SEASONAL VARIABLES

	DECLN (deg)	EQTIME (hours)	SOLCON (Btu/ft^2-hr)	ATMEXT	SKYDFF
JAN	-20.0	-.190	390	.142	.058
FEB	-10.8	-.230	385	.144	.060
MAR	0.0	-.123	376	.156	.071
APR	11.6	.020	360	.180	.097
MAY	20.0	.060	350	.196	.121
JUN	23.45	-.025	345	.205	.134
JUL	20.6	-.103	344	.207	.136
AUG	12.3	-.051	351	.201	.122
SEP	0.0	.113	365	.174	.042
OCT	-10.5	.255	378	.160	.073
NOV	-19.8	.235	387	.149	.063
DEC	-23.45	.033	391	.142	.057

$$\left.\begin{array}{l}\mathrm{tan(DECLN)}\\ \mathrm{EQTIME}\\ \mathrm{SOLCON}\\ \mathrm{ATMEXT}\\ \mathrm{SKYDFF}\end{array}\right\} = \begin{array}{l} A_0 + A_1 \cos(W) + A_2 \cos(2W) + A_3 \cos(3W) \\ + B_1 \sin(W) + B_2 \sin(2W) + B_3 \sin(3W)\end{array}$$

where W = (2π/366)IDOY; i.e., day of year converted from days to radians.

The Fourier coefficients are listed in Table III.2.

TABLE III.2

FOURIER COEFFICIENTS FOR THE SOLAR SEASONAL VARIABLES

	A_0	A_1	A_2	A_3	B_1	B_2	B_3
tan(DECLN)	-0.00527	-0.4001	-0.003996	-0.00424	0.0672	0.0	0.0
EQTIME	$0.696\,10^{-4}$	0.00706	-0.0533	-0.00157	-0.122	-0.156	-0.00556
SOLCON	368.44	24.52	-1.14	-1.09	0.58	-0.18	0.28
ATMEXT	0.1717	0.0344	0.0032	0.0024	-0.0043	0.0	-0.0008
SKYDFF	0.0905	-0.0410	0.0073	0.0015	-0.0034	0.0004	-0.0006

Equation (III.7) is obtained by setting the equation for RAYCOS(3) [Eq. (III.9)] equal to zero. That is, the solar altitude, SALT, equals zero. Then,

$$\sin(\mathrm{STALAT}) \sin(\mathrm{DECLN}) = -\cos(\mathrm{STALAT}) \cos(\mathrm{DECLN}) \cos(\mathrm{HORANG})$$

$$\mathrm{HORANG}_{sunrise} = \mathrm{GUNDOG} = \cos^{-1}[-\tan(\mathrm{STALAT}) \tan(\mathrm{DECLN})].$$

Step 2

In Eq. (III.8) the hour angle (in hours) is defined as the number of hours the present hour (solar) is from local solar noon.

IHR - 1/2 + ITIMZ - (STALON/.2618)

gives the time, corrected for the distance that the given location is from the standard meridian of the local time zone (called local civil time). Adding on the EQTIME gives the local apparent solar time, and subtracting 12 gives the hour angle in hours. Multiplying by $2\pi/24 = .2618$ converts the hour angle to radians.

Steps 3 and 4

The details and derivation of Steps 3 and 4 are addressed in the preceeding section (Brief Description) and no further explanation is necessary.

Step 5

For the derivation of the solar direction cosines, the following relations from Ref. 5, Chap. 19, are used:

sin(SALT) = sin(DECLN) sin(STALAT) + cos(DECLN) cos(STALAT) cos(HORANG),

cos(SAZM) = -[sin(DECLN) cos(STALAT) - cos(DECLN) sin(STALAT) cos(HORANG)]/cos(SALT), and

sin(SAZM) = [cos(DECLN) sin(HORANG)]/cos(SALT), (III.14)

where SAZM is the solar azimuth, measured from the south.

If a coordinate system is defined with "x" pointing west, "y" pointing south, and "z" as vertical, it can be seen from Fig. III.9 that

RAYCOS(1) = sin(SAZM) cos(SALT),

RAYCOS(2) = cos(SAZM) cos(SALT), and

RAYCOS(3) = sin(SALT). (III.15)

Substituting Eq. (III.14) into Eq. (III.15),

RAYCOS(1) = cos(DECLN) sin(HORANG),

RAYCOS(2) = -sin(DECLN) cos(STALAT) + cos(DECLN) sin(STALAT) cos(HORANG),

and

$$RAYCOS(3) = \sin(DECLN)\sin(STALAT) + \cos(DECLN)\cos(STALAT)\cos(HORANG).$$

The DOE-2 coordinate system has "x" pointing east and "y" pointing north; therefore, the sign of RAYCOS(1) and RAYCOS(2) must be changed (equivalent to a 180° rotation about "z")

$$RAYCOS(1) = -\cos(DECLN)\sin(HORANG)$$

$$RAYCOS(2) = \sin(DECLN)\cos(STALAT) - \cos(DECLN)\sin(STALAT)\cos(HORANG).$$

Last, the building azimuth must be included. This is a rotation about the "z" axis yielding

$$RAYCOS(1)_{new} = RAYCOS(1)_{old}\cos(BAZIM) - RAYCOS(2)_{old}\sin(BAZIM)$$

$$RAYCOS(2)_{new} = RAYCOS(2)_{old}\cos(BAZIM) + RAYCOS(1)_{old}\sin(BAZIM).$$

Substituting in RAYCOS(1) and RAYCOS(2) from Eq. (III.15) as $RAYCOS_{old}$, Eq. (III.9) is obtained.

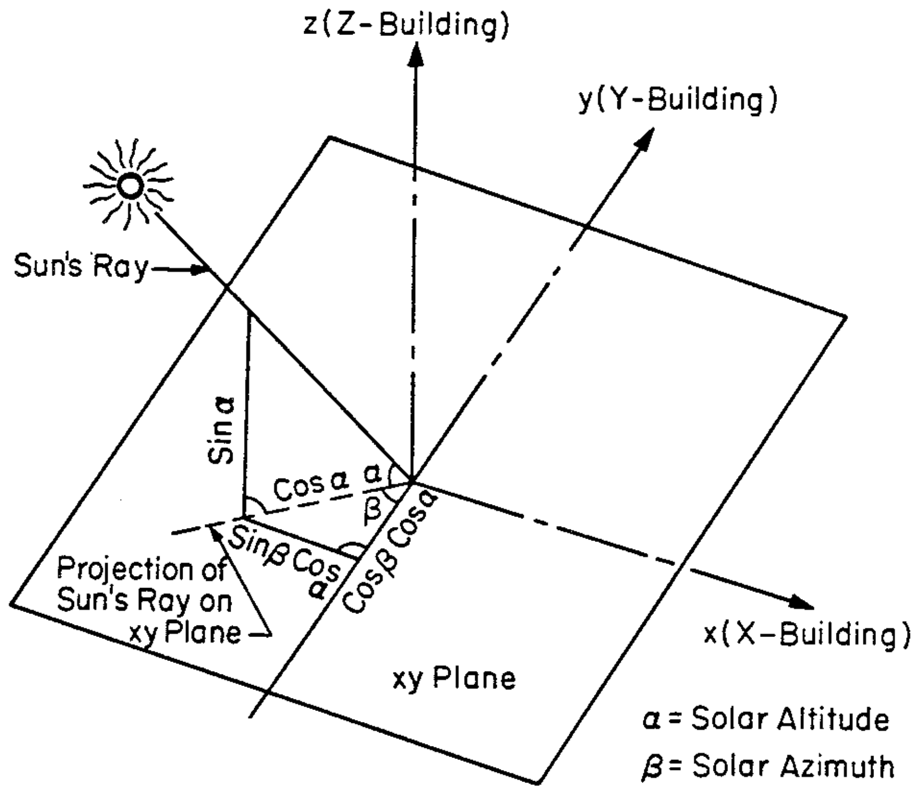


Fig. III.9. Determining the solar direction cosine.

Step 6

Equation (III.10) has the same form as Bouguer's' formula (Ref. 6, page 10),

$$RDN = I_0 P,$$

where

I_0 = solar constant, and

P = atmospheric transmittivity,

which expresses the exponential attenuation of the solar radiation by the atmosphere. The user can identify I_0 with SOLCON and P with exp(-ATMEXT). However, SOLCON < I_0, so exp(-ATMEXT) must always be greater than P. But basically, Eq. (III.10) is Bouguer's formula with coefficients obtained from measured data.

Equation (III.11) was devised by plotting measured total horizontal/direct normal radiation (DIRN) versus RAYCOS(3) and noticing that the points lay close to a straight line (Refs. 3 and 4). Hence,

$$\begin{aligned} \text{SOLRAD} &= [\text{DIRN} * \text{RAYCOS}(3)] + (\text{const} * \text{DIRN}) \\ &= [\text{DIRN} * \text{RAYCOS}(3)] + \text{BSUN} \end{aligned}$$

and

$$\text{BSUN} = \text{const} * \text{DIRN}.$$

Step 7

For cloudy days, it has been traditional to account for the reduction in solar by defining a correction factor of

$$\text{CLDCOV} = \frac{\text{total horizontal radiation}_{\text{cloudy}}}{\text{total horizontal radiation}_{\text{clear}}}$$

and then obtaining CLDCOV by comparing observed cloud amount to measured solar data. CLDCOV is usually expressed empirically as a polynomial in the cloud amount, or something closely related to the cloud amount. For DOE-2, six different polynomials are used, which correspond to three different cloud types and two regions of solar altitude. These polynomials of CLDCOV are derived from Table III.3 (Ref. 7).

TABLE III.3

COEFFICIENTS FOR CLOUD COVER FROM CLOUD AMOUNT AND CLOUD TYPE
(STRATUS, CIRRUS, AND CIRRO STRATUS CLOUDS)

ICLDTY> CLDAMT	1,STRATUS < 45	1,STRATUS > 45	0,CIRRUS < 45	CIRRO STRATUS > 45
1	.6	.88	.84	1.0
2	.6	.88	.83	1.0
3	.58	.88	.83	1.0
4	.58	.87	.82	1.0
5	.57	.85	.80	.99
6	.53	.83	.77	.98
7	.49	.79	.74	.95
8	.43	.73	.67	.90
9	.35	.61	.60	.87
10	.27	.46	.49	.74

The values in Table III.3 are fitted to the formula

$$CLDCOV = A + (B * CLDAMT) + (C * CLDAMT^2) + (D * CLDAMT^3).$$

A third cloud type, ICLDTY = 2, is defined as the average of type 0 and type 1. The coefficients are shown in Table III.4.

TABLE III.4

COEFFICIENTS FOR CLOUD COVER FROM CLOUD AMOUNT
FOR CLOUD TYPE 2

ICLDTY		A	B	C	D
1	< 45	.598	.00026	.00021	.00035
	> 45	.908	-.03214	.0102	-.00114
2	< 45	.849	-.01277	.00360	.00059
	> 45	1.01	-.01394	.00553	-.00068
3	< 45	.724	-.00625	.00191	-.00047
	> 45	.959	-.02304	.00787	-.00091

The total horizontal radiation is the sum of the direct horizontal radiation and the diffuse radiation,

$$SOLRAD_{clear\ sky} = [RDN * RAYCOS(3)] + BSUN.$$

The clear sky value is then reduced by multiplying by the cloud cover correction factor and by the fraction of the hour the sun was up.

Step 8

To separate total horizontal radiation into direct horizontal radiation (RDNCC) and diffuse radiation (BSCC), it is assumed that the direct normal solar radiation on a cloudy day varies linearly with the cloud amount from a maximum of RDN to a minimum or zero

RDNCC = RDN * (1-CLDAMT/10) * FSUNUP.

Then, the diffuse radiation is the total horizontal radiation minus the direct horizontal radiation,

BSCC = SOLRAD - [RDNCC * RAYCOS(3)].

Subdivision by Subroutine

Step 1 is done in Routine SUN1.
Steps 2 and 3 are done in WDTSUN.
Step 4 is done is CCM.
Step 5 is done in WDTSUN.

Variable List:

Program Variable	Description	HOURLY-REPORT [VARIABLE-TYPE (VARIABLE-LIST number)]
DECLN	Solar declination angle; tan(DECLN) is TDECLN.	GLOBAL(28)
EQTIME	Solar equation of time.	GLOBAL(29)
SOLCON	Fitted solar constant.	GLOBAL(30)
ATMEXT	Atmospheric extinction coefficient.	GLOBAL(31)
SKYDFF	Sky diffuse factor.	GLOBAL(32)
GUNDOG	Hour angle of sunrise.	GLOBAL(24)
HORANG	Hour angle.	GLOBAL(27)
RAYCOS(1)	Solar "x" direction cosine.	GLOBAL(33)
RAYCOS(2)	Solar "y" direction cosine.	GLOBAL(34)

Program Variable	Description	HOURLY-REPORT [VARIABLE-TYPE (VARIABLE-LIST number)]
RAYCOS(3)	Solar "z" direction cosine.	GLOBAL(35)
RDN	Direct normal solar radiation on a clear day.	GLOBAL(36)
BSUN	Diffuse solar radiation from the sky on a clear day.	GLOBAL(37)
CLRNES	Clearness number.	GLOBAL(1)
SOLRAD	Total radiation on a horizontal surface on a cloudy day (horizontal radiation).	GLOBAL(13)
CLDCOV	Cloud cover factor.	GLOBAL(20)
CLDAMT	Cloud amount in tenths.	GLOBAL(6)
RDNCC	Direct normal solar radiation on a cloudy day.	GLOBAL(21)
BSCC	Diffuse sky solar radiation on a cloudy day.	GLOBAL(22)
SALT	Solar altitude.	-
STALAT	Latitude.	-
STALON	Longitude.	-
IHR	Hour of the day.	-
FSUNUP	The fraction of the hour that the sun is up.	-
TEST	The hour angle of the hourly interval boundary nearest noon.	-
ITIMZ	Time zone.	-
SAZM	Solar azimuth, measured from south.	-
BAZIM	Building azimuth angle, measured from north to the building Y-axis.	-

2.4 Shading Calculations.

This algorithm calculates the effect of shadows cast by shading surfaces onto the exterior walls, windows, and doors of the building.

Introduction to the Bar-Polygon Method

Let shading polygon (SP) be defined as a surface that casts a shadow. The receiving polygon (RP) is defined to be the surface on which the shadow is cast. In general, several SP's with different transmittivities may cast shadows on a RP. The shadows cast by the SP's will divide the RP into a disjoint union of shadow polygons (as seen in Fig. III.10) such that the intensity of light that reaches each such shadow polygon is constant.

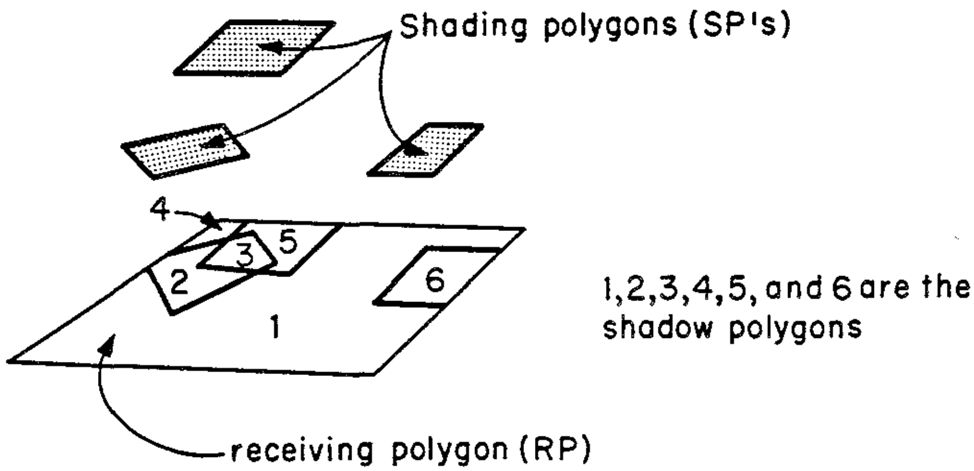


Fig. III.10. The formation of shadow polygons on a receiving polygon (RP) by shading polygons (SP's).

If an arbitrary function f(x,y) represents the intensity of sunlight on the surface of the RP, the total amount of light that reaches the entire surface of the RP is

$$\iint f(x,y)\ dx\ dy$$

where the limits of the integral are such that all points of the RP are covered.

Because the value of f(x,y) is constant for each shadow polygon, the integral of f(x,y) over a shadow polygon will simply be equal to the area of the shadow polygon times the constant value of f(x,y). The sum of such integrals for all the shadow polygons of an RP gives the total amount of light that reaches the entire surface of the RP.

In the bar-polygon method, the RP is divided into a large number of bars, or strips. The shape of each shadow polygon on the RP is approximated by calculating and storing the points where the shadow polygon crosses the midline of each bar. Thus, each shadow polygon is approximated by a group of bar segments, as shown in Fig. III.11.

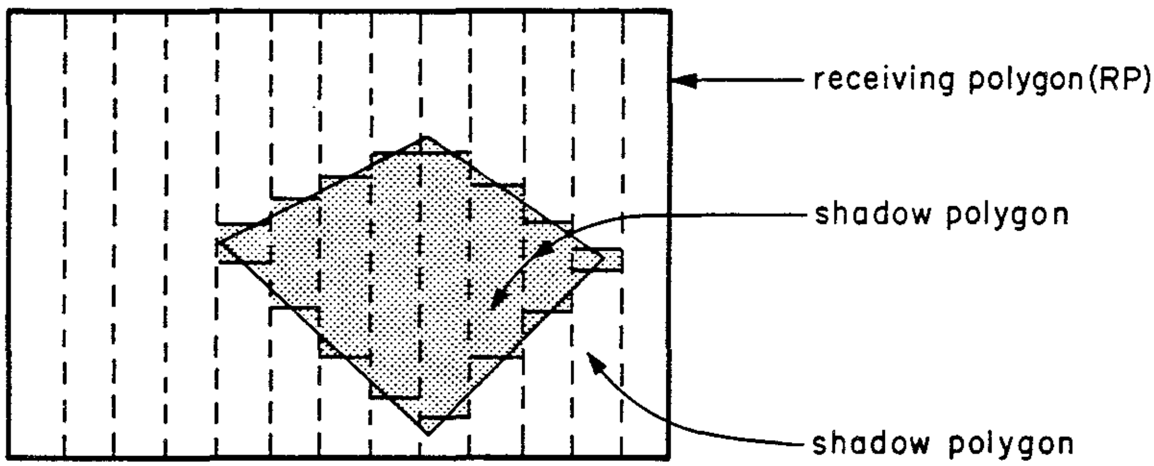


Fig. III.11. Approximating the shape of a shadow polygon on a receiving polygon.

The intensity of sunlight over each unshaded bar segment is assumed to be constant. The total amount of light that reaches the shadow polygon is then the sum of the area of each bar segment (within the shadow polygon) times the light intensity per unit area within the segment. The calculation can be made arbitrarily accurate by letting the width of the bars approach zero.

Brief Description

A brief description is now given of the algorithm as it is used in DOE-2. The algorithm is executed for one day each month of the RUN-PERIOD. The outputs are 24 shadow ratios (one for each hour of the day) for each receiving polygon. The shadow ratio is defined as

$$\frac{\text{direct solar energy striking RP when shaded}}{\text{direct solar energy striking RP when unshaded}} .$$

The shadow ratios for the same hour each day are assumed to be constant over the month.

Steps 1 through 4 are executed once for each possible RP. Steps 5 through 9 are executed once for each possible SP that can shade a RP in question.

1. A new coordinate system is defined, which is called the shadow calculation coordinate system (prime system, for short). It is embedded in the receiving polygon. The transformation from the building coordinate system to the prime system can be written

$$\begin{vmatrix} x' \\ y' \\ z' \end{vmatrix} = \begin{vmatrix} A_{11} & A_{12} & A_{13} \\ A_{21} & A_{22} & A_{23} \\ A_{31} & A_{32} & A_{33} \end{vmatrix} \begin{vmatrix} x-x_0 \\ y-y_0 \\ z-z_0 \end{vmatrix} . \qquad \text{(III.16)}$$

   The elements of the rotation matrix A_{ij} and the translation vector (x_0 y_0 z_0) are calculated.

2. The coordinates of the receiving polygon vertices are transformed from the building coordinate system to the prime system. The RP now lies in the x'y' plane.

3. The receiving polygon is enclosed in a rectangle. The rectangle is divided into bars running parallel to the y' axis. This rectangle is called the working space.

4. The solar direction cosines are transformed to the prime system. If the receiving polygon is facing away from the sun, no shading can occur and the rest of the calculation is skipped.

5. The coordinates of the shading polygon vertices are transformed to the prime system.

6. Points on the SP that are below the plane of the receiving polygon (the x'y' plane) are clipped off.

7. The clipped shading polygon is projected along the direction of the sun's incoming rays onto the plane of the receiving polygon.

8. The shape of the projected shading polygon is stored by saving the crossing points of the projected shape with the midline position of each of the bars. The crossing points divide each bar into bar segments. A relative intensity of the light reaching each bar segment is stored.

9. The bar segments and relative light intensities are used to obtain the amount of sunlight falling on the entire receiving polygon. This is used to obtain a shadow ratio for the hour.

Details and Derivation

Step 1. Derivation for transformation from the building coordinate system to the prime system.

At the start of the shadow calculations, all coordinates are in the building coordinate system. During the shadow calculations, the receiving polygon, the shading polygons, and the solar direction cosines are transformed into a new system called the shadow calculation coordinate system, or prime system. Coordinates in the building coordinate system will be denoted by (x, y, z) and coordinates in the prime system (x', y', z'). The x' and y' axes of the new system are in the plane of the receiving polygon. The x' axis passes through the vertices V_2 and V_3 of the receiving polygon. The y' axis passes through the vertex V_1 and is perpendicular to the x' axis. The z' axis is then in the direction of the cross product $\hat{x}' \times \hat{y}'$. Figure III.12 displays these relationships.

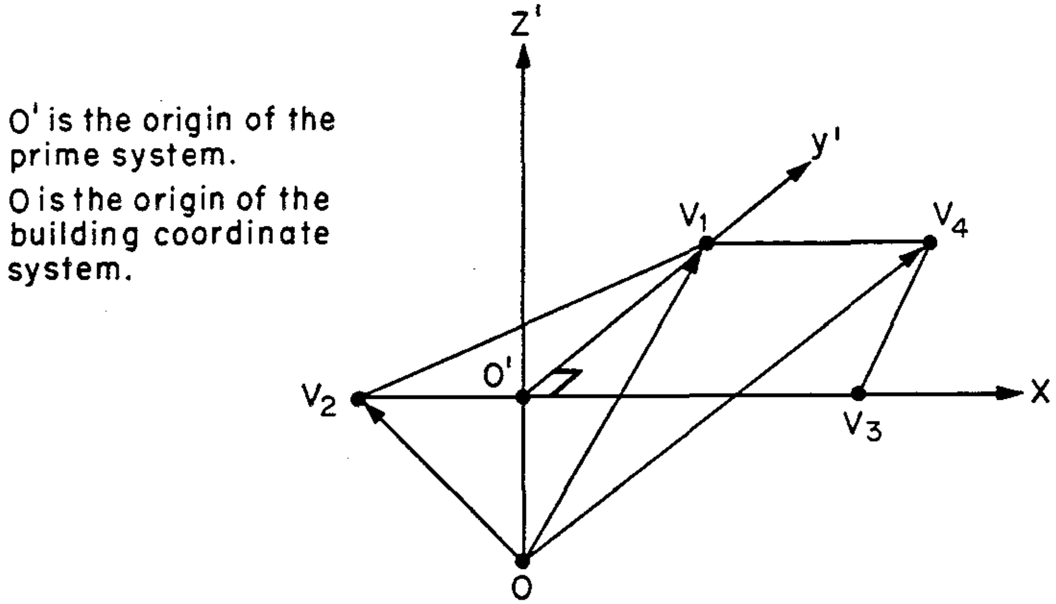


Fig. III.12. Orienting receiving polygon V_1 V_2 V_3 V_4 in the prime system.

The transformation to the prime system is done for two reasons. First, it simplifies the projection of the shading polygon onto the receiving polygon. Use of Eq. (III.16) is based on the fact that a point is in the RP plane if z' is zero. Second, after the projection is completed, the shading problem in the prime system has been reduced to two dimensions.

Transformation from the building coordinate system to the prime system involves a translation followed by a rotation, as shown in Eq. (III.16). The parameters x_0, y_0, and z_0 are the coordinates, in the building coordinate system, of the origin of the prime system. Define:

$\vec{O'}$ is the position vector of the origin of the prime system, in the building coordinate system;

$\vec{V_1}$ is the position vector of the first vertex of the RP, in the building coordinate system;

$\vec{V}_2$ is the position vector of the second vertex of the RP, in the building coordinate system; and

$\vec{V}_3$ is the position vector of the third vertex of the RP, in the building coordinate system.

Then, $\vec{V}_3 - \vec{V}_2$ is the vector running from the second vertex to the third vertex. $\vec{V}_1 - \vec{V}_2$ is the vector running from the second vertex to the first vertex.

The translation can be thought of as being done in two steps:

1. Move from 0 to V_2.
2. Move along $\vec{V}_3 - \vec{V}_2$ the distance of the projection of $\vec{V}_1 - \vec{V}_2$ on $\vec{V}_3 - \vec{V}_2$.

$$\text{That is, } \vec{O'} = \vec{V}_2 + \frac{[(\vec{V}_1 - \vec{V}_2) * (\vec{V}_3 - \vec{V}_2)]\,(\vec{V}_3 - \vec{V}_2)}{\left|\vec{V}_3 - \vec{V}_2\right|^2}.$$

In terms of coordinates,

$$x_o = x_2 + \gamma(x_3 - x_2),$$

$$y_o = y_2 + \gamma(y_3 - y_2), \text{ and}$$

$$z_o = z_2 + \gamma(z_3 - z_2)$$

where

$$\gamma = \frac{(x_1 - x_2)\,(x_3 - x_2) + (y_1 - y_2)\,(y_3 - y_2) + (z_1 - z_2)\,(z_3 - z_2)}{(x_3 - x_2)^2 + (y_3 - y_2)^2 + (z_3 - z_2)^2}.$$

The elements of the rotation matrix A_{ij} are then obtained. The first line of A_{ij} in the rotation matrix is formed by the direction cosines of the x' axis in the x-y-z system. Since the x' axis is defined to be in the direction

$$\frac{(\vec{V}_3 - \vec{V}_2)}{\left|\vec{V}_3 - \vec{V}_2\right|},$$

then

$$(A_{11}, A_{12}, A_{13}) = \frac{(x_3-x_2,\ y_3-y_2,\ z_3-z_2)}{\sqrt{(x_3 - x_2)^2 + (y_3 - y_2)^2 + (z_3 - z_2)^2}} .$$

Similarly, the second line of A_{ij} in the rotation matrix consists of the direction cosines of the y' axis in the x-y-z system. The y' axis lies along the vector $\vec{V} - \vec{O'}$ so

$$(A_{21}, A_{22}, A_{23}) = \frac{(x_1-x_0,\ y_1-y_0,\ z_1-z_0)}{\sqrt{(x_1 - x_0)^2 + (y_1 - y_0)^2 + (z_1 - z_0)^2}} .$$

The third line of A_{ij} is the cross product of the vectors defined by the first and second lines.

Step 2. Transformation of the receiving polygon vertices from the building coordinate system to the prime system.

With A_{ij} and (x_0, y_0, z_0) calculated, this step is accomplished by applying Eq. (III.16) to each vertex of the receiving polygon in turn.

Step 3. Establishing the working space and bars.

The receiving polygon now lies in the x'y' plane (see Fig. III.13). A rectangle that just encloses the polygon and whose sides are parallel to the x' and y' axes is defined. The lower x' limit, A_0, of the rectangle is the lowest x' coordinate of any of the RP vertices. A, the upper x' limit, is the highest of the x' coordinates of the RP vertices. Similarly, B_0, the lower y' limit, and B, the upper y' limit of the rectangle, are defined. The rectangle is divided into bars running parallel to the y' axis. The number of bars is controlled by user input; that is, by the keyword SHADING-DIVISION in the EXTERIOR-WALL, WINDOW, and DOOR instructions. The width of each strip is $(A - A_0)/NDIV = \Delta x$. The length is $B - B_0$. The rectangle is called the working space.

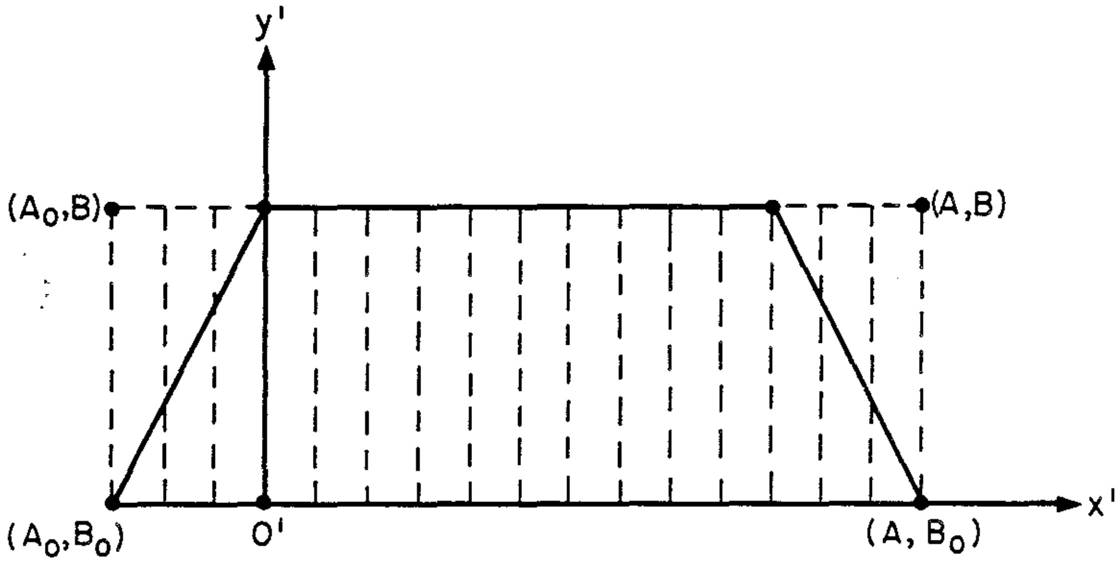


Fig. III.13. Establishing the working space with bars.

<u>Step 4. The transformation of the solar direction cosines from the building coordinate system into the prime system.</u>

The solar direction vector, at present in the building coordinate system, is transformed to the prime system by multiplying by the rotation matrix A_{ij}. A check is made on the z' component of the solar direction vector. If this is negative, the RP cannot see the sun; that is, the sun is behind the RP and no shading can occur. In this case, the rest of the steps in the algorithm are skipped. The actual check consists of determining if the sun is within one solar diameter (0.0046 radians) of being behind the RP. If the sun is, no shading will occur (see Fig. III.14).

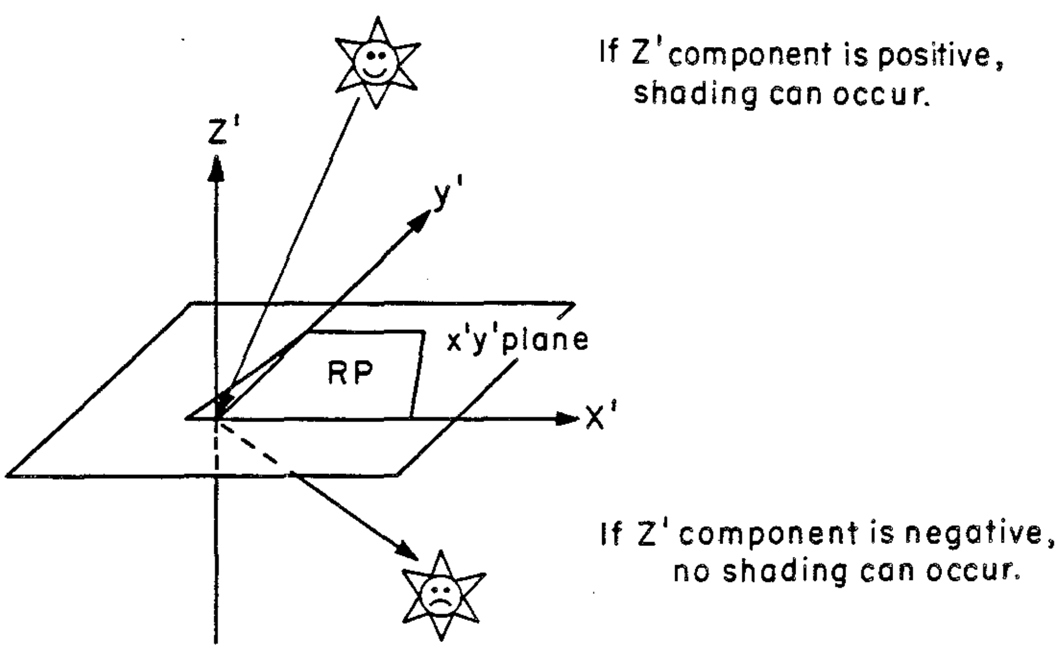


Fig. III.14. Determining if shading is possible or not.

Step 5. Transformation of the shading polygon vertices from the building coordinate system to the prime system.

The coordinates of the vertices of the shading polygons are transformed to the prime system by the application of Eq. (III.16) to each vertex in succession.

Step 6. Eliminating those portions of shading polygons that are submerged in the receiving polygon.

Those portions of each SP that are below the plane of the RP must be clipped. Otherwise, use of Eq. (III.16) will result in a false shadow being cast by the submerged portions of the SP (see Fig. III.15). Each vertex of each SP is checked. If it is below the plane of the RP (z' coordinate is negative), it is eliminated. New vertices are defined where the sides of the SP cross the RP plane (A,B). The new clipped SP is then completely above or just touching the RP plane.

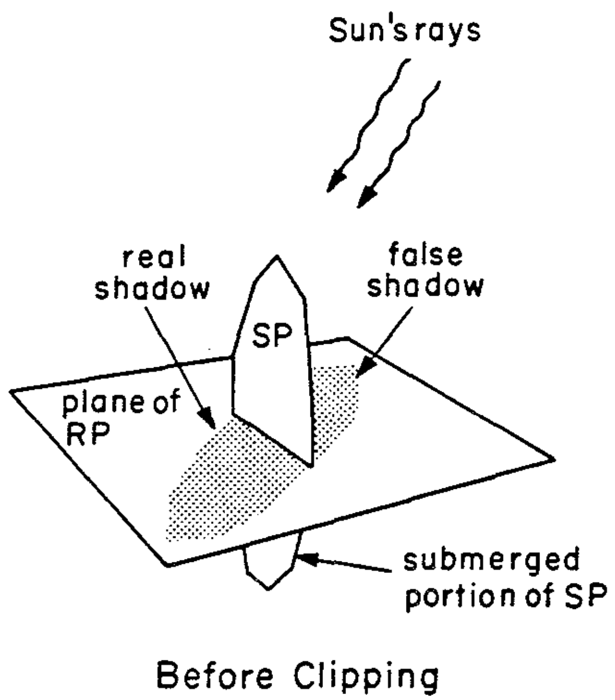


Fig. III.15. Shading polygons (SP's) submerged in the receiving polygon (RP).

Step 7. Projecting the vertices of a clipped shading polygon (SP), along the sun's ray, onto the plane of the receiving polygon (RP).

A new polygon is obtained by projecting each vertex of the clipped SP along the direction of the sun's rays onto the x'y' plane. Let P be the projected image of an SP's vertex V. The coordinates (x' y' z') of V have already been found by the coordinate transformation and clipping. The coordinates, in the prime system, of P are needed. Denote these coordinates as x'_p, y'_p, z'_p. From Fig. III.16

$$x'_p = x' - PB,$$

$$y'_p = y' - BD,$$

$$z'_p = 0.$$

Similar triangles in Fig. III.16 give

$$\frac{PB}{DV} = \frac{PA}{CE}, \text{ and}$$

$$\frac{BD}{DV} = \frac{AC}{CE}.$$

Line segment PE is the solar direction vector, so

$$PA = x'_s,$$

$$AC = y'_s, \text{ and}$$

$$CE = z'_s$$

where x'_s, y'_s, and z'_s are the solar direction cosines in the prime system.

Combining the above equations gives

$$x'_p = x' - \left(\frac{PA}{CE}\right) DV = x' - \frac{(x'_s)}{(z'_s)} z', \text{ and}$$

$$y'_p = y' - \left(\frac{AC}{CE}\right) DV = y' - \frac{(y'_s)}{(z'_s)} z'. \tag{III.17}$$

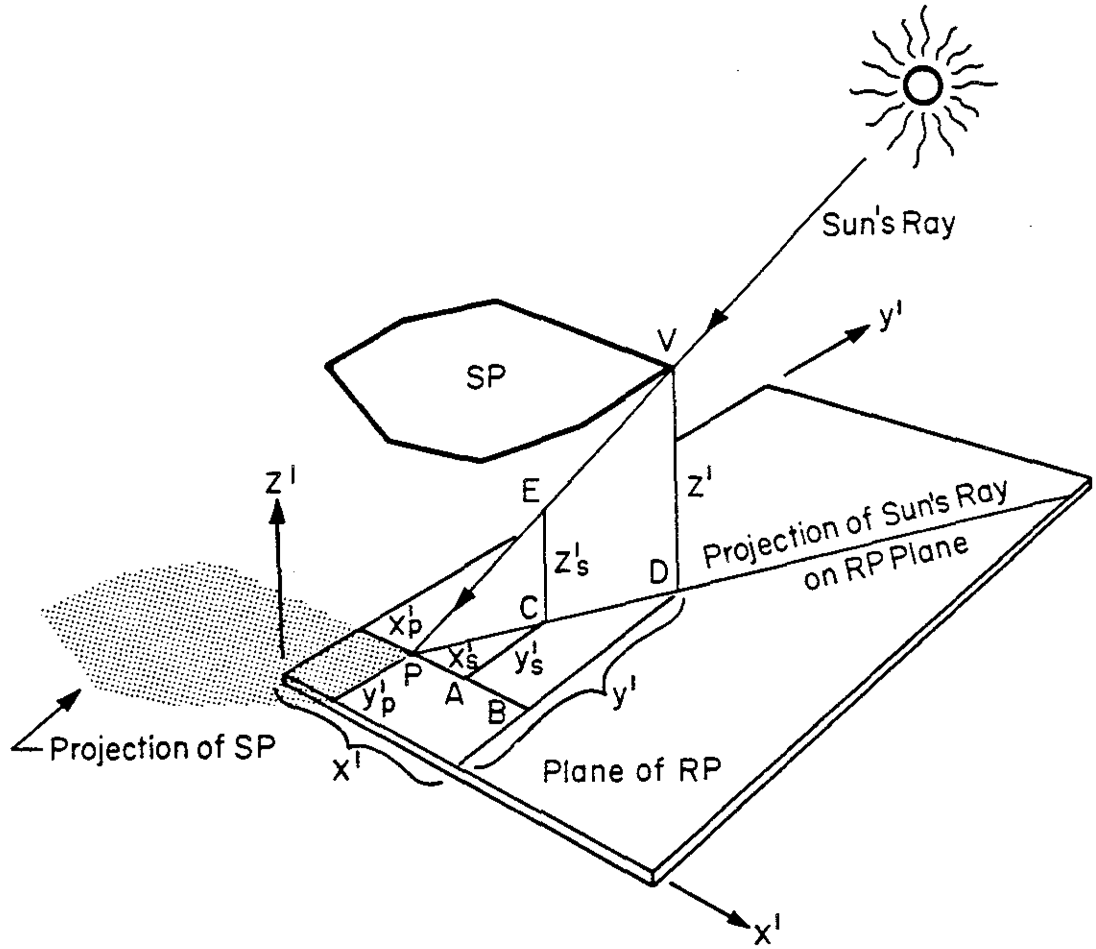


Fig. III.16. Projecting the vertex V of a shading polygon (SP), along the sun's ray, onto the plane of a receiving polygon (RP).

Step 8. Calculating and storing the shape of the projected shading polygon.

For each pair of projected vertices, P_i and P_{i+1}, on the projected shading polygon, the equation of a straight line is used to find the crossing points of the ith side of the polygon with the midlines of the bars. The y' coordinate of each such crossing point (if within the working space) is saved and merged into the set of all crossing points $\{y_{i,j}\}$ in such a way that $y_{i,j+1} > y_{i,j}$. Here i is the bar index, running from 1 to NXDIV, the number of bars specified by the user in the keyword SHADING-DIVISION; the bar index starts at 1 with the bar at A_0. The j subscript denotes the jth crossing point on the ith bar. In addition to $\{y_{i,j}\}$, a set of relative intensities $\{\tau_{i,j}\}$ is saved. $\tau_{i,j}$ is defined as the intensity of light striking the jth bar segment of the ith bar (the bar segment just above $y_{i,j}$) relative to the intensity of light on the bar segment just below it. $\tau_{i,j}$ is the transmittivity of the shading polygon if the projection of the shading polygon (i.e., the shadow) lies just above $y_{i,j}$ and the inverse of transmittivity if the shadow lies just below $y_{i,j}$. Thus, the intensity for a given bar segment can be obtained inductively by starting at the lowest bar segment (nearest B_0) in a bar and forming the product

$$I_{ij} = \prod_{k=1}^{j} \tau_{i,k}.$$

Before any SP's are projected onto the RP, the $\{y_{ij}\}$ and $\{\tau_{ij}\}$ are initialized in the following manner:

$y_{i,1}$ = B_o, the bottom of the working space,

$y_{i,4}$ = B, the top of the working space,

$y_{i,2}$ = the crossing point of the bottom of the RP with the ith bar,

$y_{i,3}$ = the crossing point of the top of the RP with the ith bar,

$\tau_{i,1}$ = SMALP = 10^{-9},

$\tau_{i,4}$ = 1/SMALP = 10^9,

$\tau_{i,2}$ = 1/SMALP = 10^9, and

$\tau_{i,3}$ = SMALP = 10^{-9}.

Initially then, the situation is as shown in Fig. III.17.

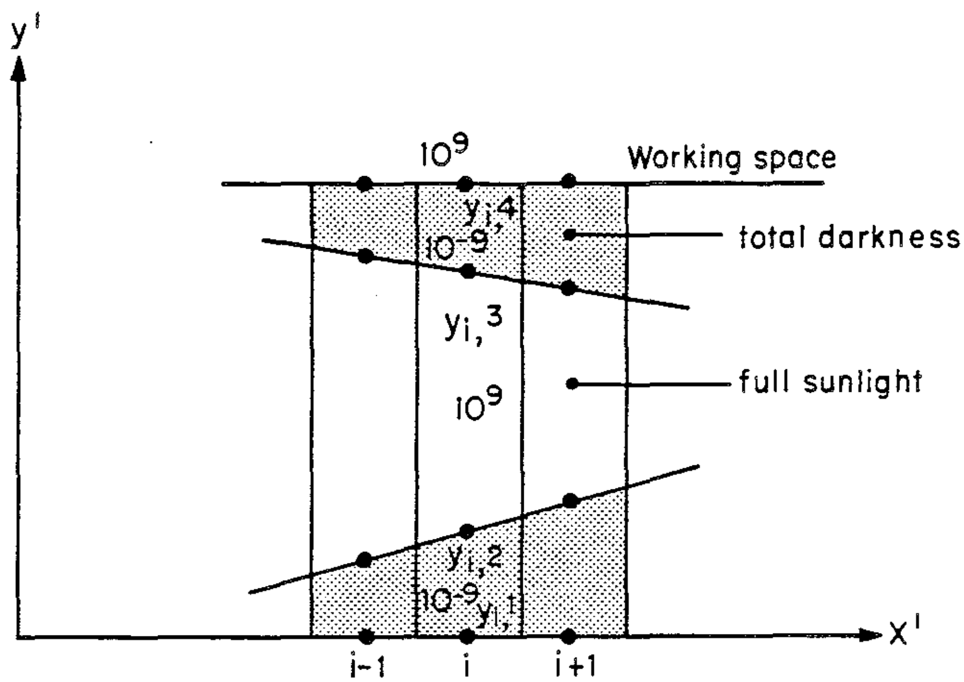


Fig. III.17. Calculating and storing the shape of the projected shading polygon plus sunlight intensity for each bar segment.

When the SP's are projected, the intensity of light within any bar segment below the SP will contain the factor SMALP = 10^{-9}, and thus be negligible. The effect of this factor is removed upon entering the RP, and is put back in for bar segments above the RP. The situation in Fig. III.17 can be thought of as showing the RP in full sunlight $[I = (10^{-9})(10^{9}) = 1]$ surrounded by the rest of the working space in total darkness ($I = 10^{-9}$). At this point, I = 1 is defined as full sunlight, i.e., unshaded.

Step 9. Calculating the total solar energy on the receiving polygon.

When all the SP's have been projected onto the RP and the sets $\{y_{i,j}\}$ and $\{\tau_{i,j}\}$ are filled and ordered, the amount of light reaching the entire RP is calculated by summing, for all bar segments in the working space, the intensity in each bar segment times the area of each bar segment,

$$\text{UNSHAR} = \Delta x \sum_{i=1}^{\text{NXDIV}} \sum_{j=2}^{\text{NEP}_i} I_{i,j-1} \, (y_{i,j} - y_{i,j-1}) \qquad \text{(III.18)}$$

where NEP_i is the number of crossing points of the ith bar, including all SP's, the RP, and the working space, and

$$I_{i,j} = \prod_{k=1}^{j} T_{i,k} = T_{i,j} \, I_{i,j-1}.$$

Notice that the last $T_{i,j}$ ($j = \text{NEP}_i$) in each bar is never used. Notice also that the quantity calculated by Eq. (III.18) has the dimensions of area. This is because all intensities have been normalized so that 1 is full sunlight. UNSHAR is the unshaded area of the RP. It is as if the RP is divided into an area in full sunlight and an area in total darkness.

The shadow multiplier is obtained by dividing the shaded area by the total area of the RP

$$\text{SM} = \frac{\text{AREA} - \text{UNSHAR}}{\text{AREA}}.$$

This multiplier is then used to multiply the amount of direct solar energy striking the unshaded surface to obtain the direct solar energy that is eliminated by shading.

Breakdown by Subroutine

Steps 1 through 4 are done in subroutine SHDWIN.
Steps 5 through 7 are done in subroutine SHDWS.
Step 8 is done in subroutine SHDWUN.
Step 9 is done in subroutine SHDWAR and subroutine SHADOW.

Definitions

x', y', z'	Coordinates in the shadow calculation or prime coordinate system.
x, y, z	Coordinates in the building coordinate system (BCS).
$A_{i,j}$	The rotation matrix used to transform from the BCS to the prime system.
x_o, y_o, z_o	The translation vector used to transform from the BCS to the prime system.
V_i	A vertex of the RP or SP.
$I_{i,j}$	The intensity (energy per unit area) of the light striking the jth bar segment of the ith bar. The intensity is defined with respect to 1 being full sunlight.
$y_{i,j}$	The jth crossing point of the ith bar of the receiving polygon.
$\tau_{i,j}$	The intensity of the jth bar segment of the ith bar relative to the j-ith bar segment.
Δx	Bar width of the receiving polygon.
NXDIV	Number of bars in the working space. This is set by the keyword, SHADING-DIVISION.
UNSHAR	Unshaded area of the RP.
SM	Shadow multiplier - EW(Variable 2), WINDOW(Variable 10), DOOR(Variable 2), i.e., the fraction of the direct solar radiation, striking the surface, that is eliminated by shading.

2.5 Interior Loads

2.5.1 Interior Heat Gains

The program keeps track of five separate interior heat gain components for each space, each hour. They are:

1. Occupancy,
2. Electrical equipment,
3. Other equipment,
4. Overhead lighting, and
5. Task lighting.

The hourly values for these five components are basically fixed by the user's input. The user assigns a peak value and a schedule for each interior heat gain component for each space.

For overhead lighting, part of the heat gain goes to the space, part to the plenum. This split is also specified by the user in the input. In the case of task lighting, all of the heat gain goes to the space.

For heat gain from equipment, the user must also specify how the heat gain component is divided into latent and sensible portions. In the case of occupant heat gain, the user can specify the split or allow the program to calculate the split. The latent heat gains are summed and passed on to the SYSTEMS program on an hourly basis. The sensible portion of the heat gains are converted to cooling loads later in the LOADS program.

In addition to keeping track of energy added to the space (heat gains), the program keeps track of the type and amount of resource consumed to produce the various heat gains. For electrical equipment, overhead lighting, and task lighting, the resource used is always electricity. For other equipment, the resource may be electricity, gas, hot water, or no resource at all (as with SOURCE-TYPE = PROCESS).

Description of Subroutines READSF and CALOTH

Steps 1 through 5 are done once for each zone. Steps 6 through 10 are done once per hour for each zone. More detailed definitions of the variables may be found at the end of this section.

1. The keywords giving peak overhead lighting in kilowatts and watts/ft^2 are combined and converted to Btu/hr

$$<ZQLT> = \left[<ZLTKW> + \left(<ZLTWSF> * \frac{<ZFLRAR>}{1000}\right)\right] * 3413.$$

Values for <ZLTKW> and <ZLTWSF> are specified by the user with the keywords LIGHTING-KW and LIGHTING-W/SQFT in the SPACE instruction. The watts/ft^2 input is converted to kilowatts by multiplying by the zone floor area (<ZFLRAR>) and dividing by 1000. The two quantities are then added together and multiplied by 3413 to convert from kilowatts to Btu/hr.

The fraction of the overhead light energy going into the space (<ZFLTH>) is specified by the LIGHT-TO-SPACE keyword in the SPACE instruction. The light energy going into the space, at peak lighting, is

<ZQLTOH> = <ZQLT> * <ZFLTH>.

The fraction of overhead lighting going to the plenum is:

<ZFRACLITE-PLENUM> = 1. - <ZFLTH>.

2. The keywords giving peak task lighting in kilowatts and watts/ft^2 are combined and converted to Btu/hr

$$<ZQTLT> = \left[<ZTLTKW> + \left(<ZTLTWSF> * \frac{<ZFLRAR>}{1000}\right)\right] * 3413.$$

Values for <ZTLTKW> and <ZTLTWSF> are input through the TASK-LIGHTING-KW and TASK-LT-W/SQFT keywords in the SPACE instruction.

3. The keywords that describe peak heat gain from electrical equipment in kilowatts and watts/ft^2 are combined and converted to Btu/hr. This quantity is then split into its latent and sensible components

$$<ZQEQ1> = \left[<ZQEQ1> + \left(<ZEQWSF> * \frac{<ZFLRAR>}{1000}\right)\right] * 3413,$$

<ZQEQ1L> = <ZQEQ1> * <ZFEQ1L>, and

<ZQEQ1S> = <ZQEQ1> * <ZFEQ1S>.

Values for <ZQEQ1> and <ZEQWSF> are input through the keywords EQUIPMENT-KW and EQUIPMENT-W/SQFT respectively in the SPACE instruction. <ZFEQ1L> and <ZFEQ1S> are the latent and sensible fractions of the equipment heat gain. They are specified by the user with EQUIP-LATENT and EQUIP-SENSIBLE keywords in the SPACE instruction.

4. Latent and sensible peak heat gains fcr other equipment are obtained

<ZQEQ2L> = <ZQEQ2> * <ZFEQ2L> and

<ZQEQ2S> = <ZQEQ2> * <ZFEQ2S>.

<ZQEQ2> is input by the SOURCE-BTU/HR keyword in the SPACE instruction. <ZFEQ2L> and <ZFEQ2S> are input with the keywords SOURCE-LATENT and SOURCE-SENSIBLE respectively.

5. In DOE-2, the user may input an all-inclusive heat gain per person (keyword PEOPLE-HEAT-GAIN) and allow the program to split it into its sensible and latent components or the user may specify the split by means of the keywords PEOPLE-HG-LAT and PEOPLE-HT-SENS. One option or the other should be chosen, but not both.

   If the user has input an all-inclusive value of heat gain for people with the keyword PEOPLE-HEAT-GAIN, an empirical formula is used to split it into sensible and latent heat gains

   PPN = <ZPPLNO>,

   PPA = <ZPPLAC> * .01,

   <ZQPPLS> = PPN {28 + PPA (266.4 - 10.25 * PPA) + (TZONER - 460)
   * [1.2 - PPA (3.07 - .128 * PPA)]}, and (III.19)

   <ZQPPLL> = PPN {206 - PPA (214.9 - 13.8 * PPA) - (TZONER - 460)
   * [6.7 - PPA (4.44 - .222 * PPA)]} where <ZPPLNO> is the number of people and <ZPPLAC> is the total (all-inclusive) heat output per person per hour.

   (III.20)

   Otherwise, the user input values for sensible and latent heat gain (PEOPLE-HG-SENS and PEOPLE-HG-LAT respectively) are used

   <ZQPPLS> = PPN * <ZPPLS> and

   <ZQPPLL> = PPN * <ZPPLL>.

   People lose heat from their skin by convection and radiation, which will become a sensible heat gain and by the evaporation of perspiration, which will be a latent heat gain. The relative size of the sensible and latent heat gains for a person are a function of the person's overall metabolic rate (how hard he is working) and the temperature of the environment.

   Equations (III.19) and (III.20) are derived from Figures 6 and 7 in Chapter 6 of the 1960 ASHRAE GUIDE. The figures plot the sensible and latent heat loss of an average man as a function of dry-bulb temperature for five different total metabolic rates. The portions of the curves between 70°F and 80°F were fit to a straight line

   A + (B * DBT) (III.21)

and five values of A and B were obtained for both latent and sensible heat loss. A quadratic curve was then fit through the five values of A and B, yielding

$$A = 28 + 266.40Q_m - 10.250Q_m^2 \text{ and}$$

$$B = 1.2 - 3.07Q_m + .1280Q_m^2$$

for sensible, and

$$A = 206 - 214.9Q_m - 13.8Q_m^2$$

$$B = -6.7 + 4.44Q_m - .222Q_m^2$$

for latent. Here Q_m stands for total metabolic rate in Btu/hr. Substituting A and B into Eq. (III.21) gives Eqs. (III.19) and (III.20). Because the temperature range used in the fit was 70°-80°F and the five total metabolic curves range from 400 to 1310 Btu/hr, Eqs. (III.19) and (III.20) will only produce correct results inside this range. For conditions outside this range, the keywords PEOPLE-HG-LAT and PEOPLE-HG-SENS should be used.

The following steps are performed once each hour for each zone:

6. If the user has input an occupancy schedule, the hourly heat gain from people is obtained by multiplying the peak heat gains (<ZQPPLS> and <ZQPPLL>) by the hourly schedule value [SV(ISCHR)]

QPPS = SV(ISCHR) * <ZQPPLS> and

QPPL = SV(ISCHR) * <ZQPPLL>.

The schedule for occupancy is assigned by the PEOPLE-SCHEDULE keyword in the SPACE instruction.

If no occupancy schedule has been input

QPPS = 0. and

QPPL = 0.

7. If the user has input a schedule for "other" equipment, the hourly heat gains from this equipment are obtained

QEQPS2 = SV(ISCHR) * <ZQEQ2S> and

QEQPL2 = SV(ISCHR) * <ZQEQ2L>.

The schedule for other equipment is assigned by the SOURCE-SCHEDULE keyword in the SPACE instruction. The type of resource consumed is specified by the SOURCE-TYPE keyword.

If no schedule was input, QEQPS2 = QEQPL2 = 0. The program keeps track of resource usage:

if electricity is being used, QZEQEL = SV(ISCHR) * <ZQEQ2>, and QELECT = QZEQEL,

if gas is being used, QZGAS = SV(ISCHR) * <ZQEQ2>,

if hot water is used, QZHW = SV(ISCHR) * <ZQEQ2>, and

if no schedule was input, QZEQEL = QELECT = QZGAS = QZHW = 0.

where <ZQEQ2> is the zone peak for other equipment that was specified for SOURCE-BTU/HR. The energy for SOURCE-TYPE = PROCESS is not included above because its resource demand is not passed to PLANT; only its contribution to the space load is calculated as SV(ISCHR) * <ZQEQ2>.

8. If the user has input a schedule for electrical equipment, the hourly heat gains are

QEQPS = SV(ISCHR) * <ZQEQ1S> and

QEQPL = SV(ISCHR) * <ZQEQ1L>.

The schedule for electrical equipment is assigned by the EQUIP-SCHEDULE keyword in the SPACE instruction.

Energy consumed this hour is accounted for

QELECT = QELECT + [SV(ISCHR) * <ZQEQ1>] and

QZEQEL = QZEQEL + [SV(ISCHR) * <ZQEQ1>].

If no schedule was input, QEQPS = QEQPL = 0 and QELECT and QZEQEL are not incremented.

9. If the user has input an overhead lighting schedule, the electricity used in each zone each hour by overhead lighting (QZLTEL) is added to the variables that are keeping track of the space electrical use

QZLTEL = SV(ISCHR) * <ZQLT> and

QELECT = QELECT + QZLTEL.

The lighting schedule is assigned by means of the LIGHTING-SCHEDULE keyword in the SPACE instruction.

If the user has input an overhead lighting schedule, the heat gain to the space (QLITE) and to the plenum (QPLENM) are calculated

QLITE = SV(ISCHR) * <ZQLTOH> and

QPLENM = QLITE * <ZFRACLITE-PLENUM>.

If no overhead lighting schedule was input, QZLTEL = QLITE = QPLENM = 0.

10. If the user has input a task lighting schedule, the heat gain from task lighting is calculated and the energy used is added to the space electrical use

QELECT = QELECT + [SV(ISCHR) * <ZQTLT>],

QZLTEL = QZLTEL + [SV(ISCHR) * <ZQTLT>], and

QTSKL = SV(ISCHR) * ZQTLT.

The task lighting schedule is input by the TASK-LIGHTING-SCH keyword in the SPACE instruction.

If no task lighting schedule was input, QTSKL = 0 and QELECT and QZLTEL are not incremented.

<u>Breakdown by Subroutine</u>

Steps 1 through 5 are in subroutine READSF.
Steps 6 through 10 are in subroutine CALOTH.

<u>Definitions</u>

<ZQLT>	The peak energy from overhead lights entering the space and plenum in an hour. (Btu/hr)

<ZLTKW>	The peak energy from overhead lights entering the space and plenum in an hour, as input by the LIGHTING-KW keyword in the SPACE instruction. (KW)
<ZLTWSF>	The peak energy from overhead lights entering the space and plenum in an hour, as input by the LIGHTING-W/SQFT keyword in the SPACE instruction. (watts/ft^2)
<ZFLRAR>	The floor area of the space as specified by the AREA keyword or by the keywords WIDTH and DEPTH in the SPACE instruction. (ft^2)
<ZQLTOH>	The part of the peak energy from the overhead lights going to the space and not to the plenum. (Btu/hr)
<ZFLTH>	The fraction of the overhead lighting energy going to the space and not to the plenum. This is input by the LIGHT-TO-SPACE keyword in the SPACE instruction.
<ZFRACLITE-PLENUM>	Fraction of the overhead lighting going to the plenum.
<ZQTLT>	The peak energy from task lighting entering the space in an hour. (Btu/hr)
<ZTLTKW>	The peak energy from task lighting entering the space per hour, as input by the TASK-LIGHTING-KW keyword in the SPACE instruction.
<ZTLTWSF>	The peak energy from task lighting entering the space per hour, as input by the TASK-LT-W/SQFT keyword in the SPACE instruction. (watts/ft^2)
<ZQEQ1>	The peak energy from electrical equipment entering the space per hour, as input by the EQUIPMENT-KW keyword in the SPACE instruction. The same variable (<ZQEQ1>) is used for the peak energy of electrical equipment entering the space per hour in Btu/hr (the sum of the inputs through the keywords EQUIPMENT-KW and EQUIPMENT-W/SQFT).
<ZEQWSF>	The peak energy from electrical equipment entering the space per hour, as input by the EQUIPMENT-W/SQFT keyword in the SPACE instruction. (watts/ft^2)
<ZQEQ1L>	The peak latent energy from electrical equipment entering the space per hour. (Btu/hr)
<ZFEQ1L>	The fraction of the electrical equipment energy that is in the form of latent heat, as input by the EQUIP-LATENT keyword in the SPACE instruction.
<ZQEQ1S>	The peak sensible energy from electrical equipment entering the space per hour. (Btu/hr)

<ZFEQ1S> The fraction of the electrical equipment energy that is in the form of sensible heat, as input by the EQUIP-SENSIBLE keyword in the SPACE instruction.

<ZQEQ2L> The peak latent energy entering the space per hour from other equipment or processes, as input by the SOURCE group of keywords. (Btu/hr)

<ZQEQ2> The peak energy entering the space per hour from other equipment or processes, as input by the SOURCE-BTU/HR keyword in the SPACE instruction. (Btu/hr)

<ZFEQ2L> The fraction of SOURCE-BTU/HR that is in the form of latent heat. This is input by the SOURCE-LATENT keyword in the SPACE instruction.

<ZQEQ2S> The peak sensible energy entering the space per hour from other equipment or processes, as input by the SOURCE group of keywords. (Btu/hr)

<ZFEQ2S> The fraction of SOURCE-BTU/HR that is in the form of sensible heat. This is input by the SOURCE-SENSIBLE keyword in the SPACE instruction.

PPN The peak number of people in the space. This is equivalent to the keyword NUMBER-OF-PEOPLE in the SPACE instruction.

<ZPPLNO> Same as PPN.

<ZPPLAC> The total peak heat output per person per hour. Equivalent to the value specified for the keyword PEOPLE-HEAT-GAIN. (Btu/hr)

<ZQPPLS> The peak sensible heat gain in the space from people. (Btu/hr)

<ZQPPLL> The peak latent heat gain in the space from people. (Btu/hr)

TZONER The zone temperature in °R.

<ZPPLS> The peak sensible heat gain in the space per person. This is equivalent to the value specified for the keyword PEOPLE-HG-SENS in the SPACE instruction. (Btu/hr)

<ZPPLL> The peak latent heat gain in the space per person. This is equivalent to the value specified for the keyword PEOPLE-HG-LAT in the SPACE instruction. (Btu/hr)

SV Stands for an hourly schedule value.

ISCHR The present schedule hour.

QPPS	The sensible heat gain in the space from people. (Btu/hr) SPACE(12)
QPPL	The latent heat gain in the space from people. (Btu/hr) SPACE(28)
QEQPS2	The sensible heat gain in the space from other equipment or processes input through the SOURCE group of keywords. (Btu/hr) SPACE(11)
QEQPL2	The latent heat gain in the space from other equipment or processes input through the SOURCE group of keywords. (Btu/hr) SPACE(30)
QZEQEL	The amount of electrical energy consumed by equipment or processes, other than lighting, in the space this hour. (Btu/hr) SPACE(46)
QELECT	The total amount of electricity used in the space (and plenum) this hour. (Btu/hr) SPACE(38)
QZGAS	The amount of gas used in the space this hour. (Btu/hr) SPACE(47)
QZHW	The amount of hot water used in the space this hour. (Btu/hr) SPACE(48)
QEQPS	The sensible heat gain from electrical equipment (excluding all contributions from the SOURCE keywords) in the space this hour. (Btu/hr) SPACE(10)
QEQPL	The latent heat gain from electrical equipment (excluding all contributions from the SOURCE keywords) in the space this hour. (Btu/hr) SPACE(29)
QZLTEL	The amount of electricity used by lighting in the space and plenum this hour. (Btu/hr) SPACE(45)
QLITE	The heat gain from overhead lights in the space this hour. (Btu/hr) SPACE(35)
QPLENM	The heat gain from overhead lights in the plenum this hour. (Btu/hr) SPACE(15)
QTSKL	The sensible heat gain from task lighting in the space this hour. (Btu/hr) SPACE(13)

2.5.2 Calculation of Cooling Loads from Heat Gains

This section describes how the LOADS program uses weighting factors to convert heat gains into cooling loads. The "heat gain" of a space, or room, is defined as the amount of energy entering the space in an hour. The "cooling load" is defined as the amount of energy that must be removed from the space to maintain the space air temperature at a fixed value. The cooling load is not equal to the heat gain because the portion of the heat gain that is radiant energy can be absorbed by the walls and furniture and enter the room air during a later hour. The weighting factors are a representation of the transfer function between the heat gain and the cooling load. The cooling load is the output of the LOADS program. Cooling loads for each space are passed to the SYSTEMS program on an hourly basis.

Brief Description

Heat gains are converted to cooling loads by the formula

$$CL(t_i) = \gamma_0 HG(t_i) + \gamma_1 HG(t_{i-1}) + \gamma_2 HG(t_{i-2}) - W_1 CL(t_{i-1}) - W_2(t_{i-2}). \qquad \text{(III.22)}$$

Details and Derivation

A heat gain component is defined as the heat gain coming from a particular source. LOADS keeps track of seven separate heat gain components:

1. conduction heat gain, subdivided into:

    a. quick walls,
    b. quick roofs,
    c. windows,
    d. delayed walls,
    e. delayed roofs,
    f. interior walls,
    g. underground floors,
    h. underground walls, and
    i. doors,

2. solar heat gain,

3. heat gain from lights,

4. heat gain from task lighting,

5. heat gain from equipment,

6. heat gain from other equipment, and

7. occupancy heat gain.

Each of these heat gain components is separately converted to a cooling load component by the application of Eq. (III.22).

Equation (III.22) represents the application of a transfer function to an input (the heat gain) to produce an output (the cooling load). Because the heat gains are in discrete (hourly) form, the z-transform method is used. (See Sec. II.2 of this manual for a discussion of the z-transform technique and further references.) The most economical expression of the z-transfer function is as the ratio of two polynomials:

$$K(z) = \frac{\gamma_0 + \gamma_1 z^{-1} + \gamma_2 z^{-2} + \dots}{w_0 + w_1 z^{-1} + w_2 z^{-2} + \dots}, \tag{III.23}$$

then,

$$CL(z) = K(z)\ HG(z) \tag{III.24}$$

where $CL(z)$ is the z-transform of the cooling load and $HG(z)$ is the z-transform of the heat gain. When Eq. (III.24) is inverted, we have the general form of Eq. (III.22):

$$w_0\ CL(t_i) = \sum_{j=o}^{n} \gamma_j\ HG(t_{i-j}) - \sum_{j=1}^{n} W_j\ CL(t_{i-j}). \tag{III.25}$$

That is, the cooling load for the present hour (t_i) is expressed in terms of the cooling load for the previous hours and the heat gain for the present and previous hours. The coefficients γ_j and W_j are called the weighting factors.

The value of n to use in Eq. (III.25) depends on the characteristics of the system being modeled. If the response curve of the system to a pulse input is a simple exponential, n = 1. If the system response curve is the sum of two exponentials, n = 2. For modeling rooms, n = 2 has been found to be adequate for most cases (Ref. 8). This limit (n = 2), however, will be inadequate for rooms with very massive walls or rooms that have Trombe or water walls. When the model is inadequate, the cooling loads summed over a month or year will be correct, but the size and time of the cooling load peak will be incorrect.

Weighting factors will differ from room to room and from heat gain component to heat gain component. The differences from room to room result from differences in room geometry, wall construction, fenestration, and orientation (Refs. 9, 10, and 11). The differences between heat gain components within a given room are caused by differences in how the heat gain component is divided into radiant and convective energy and how the radiant portion of the energy is divided among the room surfaces. In DOE-2, five different sets of weighting factors are used for the seven heat gain components. They are:

1. conductive weighting factors,
2. solar heat gain weighting factors,
3. weighting factors for light,
4. weighting factors for task lighting, and
5. people and equipment weighting factors.

Thus, heat gain components 5 through 7 are handled by the same set of weighting factors.

The various radiative-convective splits used in the derivation of the weighting factors are given in Sec. II.2.3.4. The distribution of radiant energy among the room surfaces for the solar heat gain weighting factors is defined by the user by means of the SOLAR-FRACTION keyword in the EXTERIOR-WALL, ROOF, INTERIOR-WALL, UNDERGROUND-WALL, and UNDERGROUND-FLOOR instructions during a weighting-factor calculation. All other weighting-factor sets are produced assuming the radiant portion of the heat gain is distributed isotropically.

The heat gain of a plenum is transformed into a cooling load by means of the weighting-factor for lights.

Finally, it should be noted that the user may choose to use either custom weighting factors (by use of the WEIGHTING-FACTOR keyword or by specifying FLOOR-WEIGHT = 0 in the SPACE or SPACE-CONDITIONS instructions) or precalculated weighting factors (by specifying the FLOOR-WEIGHT $\neq$ 0 in the SPACE or SPACE-CONDITIONS instructions). For precalculated weighting factors $n = 1$ in Eq. (III.25); i.e., $\gamma_2 - W_2 = 0$ in Eq. (III.22).

Breakdown by Subroutine

Step 1 is done in subroutine CALOTH.

Definitions

$CL(t_i)$	Cooling load for the present hour.
$HG(t_i)$	Heat gain for the present hour.
$CL(t_{i-j})$	Cooling load for the jth previous hour.
$HG(t_{i-j})$	Heat gain for the jth previous hour.
γ_i, W_i	Weighting factors.
$K(z)$	z-transfer function relating heat gains to cooling loads.
$CL(z)$	z-transform of cooling load.
$HG(z)$	z-transform of heat gain.

2.6. Heat Conduction Gain

2.6.1. Heat Conduction Through Quick Walls and Doors

This algorithm is used to calculate the heat flow through a wall or door that has no heat capacity (that is, a transient or steady-state construction). The heat flow is affected by wind speed, outside surface roughness, radiation, reradiation, absorptivity of the outside surface of the wall, the surface temperatures on both sides of the wall, and wall area.

Discussion:

Step 1

The effect of wind speed on convection and radiation from the outside surface of the wall can be expressed by a combined radiative-convective film coefficient, FILMU. This film coefficient is expressed as a 2nd order polynomial in the wind speed. Different sets of coefficients are used in the polynomial for different surface roughnesses. The polynomial coefficients were derived from experimental data, which was obtained from tests made on 12-in-square samples at mean temperatures of 20°F and for wind speeds up to 40 mph (Ref. 12). The conductances include a radiative portion of about 0.7 Btu/hr-ft^2-°F. The curves are plotted in Ref. 1, page 22.2, Fig. 1. The formula used is

$$FILMU = A + (B * WNDSPD) + (C * WNDSPD^2). \qquad (III.26)$$

The values of wind speed, WNDSPD, are taken from the weather file and the coefficients A, B, and C are

<ISURRO>	A	B	C
1	2.04	.535	0.
2	2.20	.369	.001329
3	1.90	.380	0.
4	1.45	.363	-.002658
5	1.80	.281	0.
6	1.45	.302	-.001661.

<ISURRO> is a number from 1 to 6 that characterizes the type of surface. It is specified by the user as a value, from 1 through 6, for the keyword ROUGHNESS, which is in the CONSTRUCTION command. The surface types are

1 stucco,
2 brick and rough plaster,
3 concrete,
4 clear pine,
5 smooth plaster, and
6 glass, white paint on pine.

Thus, 1 is the roughest surface and 6 is the smoothest.

The wind speed in the formula should be the air velocity near the surface. In fact, the program uses the wind speed from the weather file, which is not a very accurate estimate of the wind speed near the building surfaces.

Step 2

The long wave reradiation to the sky is estimated by assuming that the clear sky reradiation from a horizontal surface should be 20 Btu/hr-ft^2 (Refs. 13 and 14). When the sky is covered by clouds, the assumption is made that no reradiation occurs; i.e., that the clouds and the surface are at approximately the same temperature. For partial cloud covers, a linear interpolation is made, expressed as

$$SKYA = 2\ (10 - CLDAMT). \tag{III.27}$$

Step 3

The heat balance equation at the outside surface can be written

$$q_{out} = q_1 + q_2 - q_3,$$

where

q_1 = the energy absorbed by the surface from direct solar radiation, diffuse sky radiation, and short wave radiation reflected from the ground; that is, q_1 = SOLI * <SURABSO>,

q_2 = energy from convective and long wave interchange with the air; that is, q_2 = FILMU * (DBTR - T), and

q_3 = long wave reradiation. That is, the difference between the long wave radiation incident on the surface, from the sky and the ground, and the radiation emitted by a black body at the outdoor air temperature. For a horizontal surface, q_3 = SKYA. For a vertical surface, which sees both sky and ground, the net reradiation is assumed to be zero. Intermediate tilts are calculated by a linear interpolation in the cosine of the tilt angle of the wall or door. Thus, q_3 = SKYA * MAX(GAMMA, 0).

For a wall with no heat capacity, the heat flow at the outside surface must equal the heat flow at the inside surface, therefore,

$$q_{in} = q_{out} = U * (T - TZONER). \tag{III.28}$$

Here, U is the combined conductance of the wall and the inside film. Thus,

$$U(T-TZONER) = (SOLI*\langle SURABSO\rangle) + [FILMU*(DBTR-T)] + [SKYA*MAX(GAMMA,0].$$

Solving for T, the outside wall surface temperature, yields

$$T = \frac{(SOLI*\langle SURABSO\rangle) + (FILMU*DBTR) - [SKYA*MAX(GAMMA,0)] + (U*TZONER)}{U + FILMU}. \tag{III.29}$$

Step 4

Once T is known, the total heat flow at the inside surface is Eq. (III.28) multiplied by the surface area, or

$$Q = U * XSAREA * (T - TZONER). \tag{III.30}$$

Subdivision by Subroutine

Step 1 is done in function FILM.
Step 2 is done in the first part of WDTSUN.
Steps 3 and 4 are done in CALEXT.

Variable List:

Program Variable	Description	HOURLY-REPORT [VARIABLE-TYPE (VARIABLE-LIST number)]
FILMU	The combined radiative and convective outside surface conductance in Btu/(hr-ft2-°F).	E-W(3), DOOR (1)
WNDSPD	Wind speed in knots.	GLOBAL(16)
CLDAMT	Cloud amount in tenths.	GLOBAL(06)
SKYA	Heat loss by horizontal surface to sky in Btu/(hr-ft2).	GLOBAL(23)

Program Variable	Description	HOURLY-REPORT [VARIABLE-TYPE (VARIABLE-LIST number)]
T	Outside surface temperature (°R).	E-W(6), DOOR(4)
SOLI	Solar radiation incident on outside wall surface from direct, diffuse, and reflected radiation in Btu/(hr-ft^2).	E-W(1), DOOR(3)
<SURABSO>	Surface absorptivity. This is the same as the keyword ABSORPTANCE in the CONSTRUCTION command.	-
DBTR	Outside air temperature (°R).	GLOBAL(24)
GAMMA	Cosine of wall tilt.	-
U	Conductance of the wall exclusive of the outside air film (includes a combined inside film coefficient) -- Btu/(hr-ft^2-°F). This is the same as the keyword U-VALUE in the CONSTRUCTION command.	-
TZONER	The constant space temperature (°R). This is the keyword TEMPERATURE in the SPACE command, converted from Fahrenheit to Rankine.	-
Q	Heat flow through the inside surface Btu/hr.	E-W(5), DOOR(5)
XSAREA	Surface area (ft^2).	-
<ISURRO>	Surface roughness. The same as the keyword ROUGHNESS in the CONSTRUCTION command.	-

2.6.2. Heat Conduction Through Delayed Walls.

This algorithm is used to calculate the heat flow through a wall with a finite heat capacity. The structure is the same as for quick walls, except that the wall is described by a set of response factors, rather than a U-value. (It is not possible to specify doors by this method.)

The heat flow through delayed walls is affected by the same parameters as quick walls and doors (that is, wind speed, outside surface roughness, radiation, reradiation, absorptivity of the outside surface of the wall, the surface temperature on both surfaces, and wall area). Additionally, delayed wall heat flow is affected by the wall materials and their configuration in the wall.

Discussion:

Step 1

The outside combined (radiative and convective) film coefficient, FILMU, is obtained in the same manner as for quick walls (see Sec. III.2.6.1).

Step 2

The reradiation term, SKYA, is obtained in the same manner as for quick walls (see Sec. III.2.6.1).

Step 3

The heat balance equation at the outside wall surface must be solved for T, the outside surface temperature. From the definition of response factors (see Sec. II.1):

$$QOUT_t = \left[\sum_{j=0}^{\infty} TOUT_{t-j}\ X_j\right] - \left[\sum_{j=0}^{\infty} TIN_{t-j}\ Y_j\right]$$

and

$$QIN_t = \left[\sum_{j=0}^{\infty} TOUT_{t-j}\ Y_j\right] - \left[\sum_{j=0}^{\infty} TIN_{t-j}\ Z_j\right],$$

where

$QOUT_t$ = heat flow through the outside surface during the present hour (t),

QIN_t = heat flow through the inside surface during the present hour (t),

$TOUT_{t-j}$ = the temperature at the outside surface during the jth previous hour,

TIN_{t-j} = the temperature at the inside surface during the jth previous hour, and

$\left.\begin{matrix} X_j \\ Y_j \\ Z_j \end{matrix}\right\}$ = the response factors for the wall.

By subtracting the constant room temperature, TZONER, inside the sums in each equation:

$$QOUT_t = \left[\sum_{j=0}^{\infty} (TOUT_{t-j} - TZONER)X_j\right] - \left[\sum_{j=0}^{\infty} (TIN_{t-j} - TZONER)Z_j\right].$$

TIN_t, the inside surface temperature, has now been distinguished from the space air temperature, TZONER. As written in the above equation, the response factors characterize the wall from the outside surface to the inside surface, not including any film coefficients. To simplify the equations, it is possible to redefine the response factors to include the inside film resistance. Then, TIN_{t-j} = TZONER and half of the terms drop out leaving,

$$QOUT_t = \sum_{j=0}^{\infty} (TOUT_{t-j} - TZONER)\ X_j,$$

and by the same reasoning

$$QIN_t = \sum_{j=0}^{\infty} (TOUT_{t-j} - TZONER)\ Y_j.$$

QIN_t is now the heat flow <u>inside</u> the inside film coefficient. For calculational purposes, the infinite sums are unwieldy and must be replaced by finite sums. From the derivation and definition of response factors, it is shown that the X_j, Y_j, and Z_j series will eventually reach a common ratio:

$$X_{k+1} = \langle RFCOMR\rangle * X_k,$$

where <RFCOMR> is a constant and is the same for Y_j and Z_j. Thus, it can be written

$$QOUT_t = \left[\sum_{j=0}^{k} (TOUT_{t-j} - TZONER)X_j\right] + X_k\left[\sum_{j=1}^{\infty} \langle RFCOMR\rangle^j\ (TOUT_{t-k-j} - TZONER)\right].$$

Substituting t-1 for t in the above equation,

$$QOUT_{t-1} = \left[\sum_{j=0}^{k} (TOUT_{t-1-j} - TZONER) X_j \right]$$

$$+ X_k \left[\sum_{j=1}^{\infty} <RFCOMR>^j \, (TOUT_{t-1-k-j} - TZONER) \right].$$

Then, subtracting and rearranging

$$QOUT_t = \left[<RFCOMR> \; QOUT_{t-1} \right] + \left[X_0 \, (TOUT_t - TZONER) \right]$$

$$+ \sum_{j=1}^{k} \left[X_j - (<RFCOMR> \; X_{j-1}) \right] (TOUT_{t-j} - TZONER).$$

The quantity $X_j' = X_j - (<RFCOMR> \; X_{j-1})$ with $X_0' = X_0$ can be called a modified response factor. Then,

$$QOUT_t = \left[<RFCOMR> \; QOUT_{t-1} \right] + \left[\sum_{j=0}^{k} X_j' \, (TOUT_{t-j} - TZONER) \right].$$

The same manipulation for QIN_t gives

$$QIN_t = \left[<RFCOMR> \; QIN_{t-1} \right] + \left[\sum_{j=0}^{k} Y_j' \, (TOUT_{t-j} - TZONER) \right],$$

where

$$Y_j' = Y_j - (<RFCOMR> \; Y_{j-1})$$

and

$$Y_0' = Y_0.$$

The goal of replacing the infinite sums with finite sums has been met by means of saving the previous hour's quantities QIN_{t-1} and $QOUT_{t-1}$. The X_j' and Y_j' (modified response factors) can be precalculated from X_j and Y_j. Then, the equation for $QOUT_t$ can be solved for $TOUT_t = T$, and the equation for QIN_t used to obtain $Q = QIN_t * XSAREA$. In fact, the above manipulation can be extended indefinitely. It is possible to define

$$QOUT_t' = QOUT_t - (\langle RFCOMR\rangle * QOUT_{t-1}) = \sum_{j=0}^{k} X_j' \,(TOUT_{t-j} - TZONER).$$

The series X_j' will have a common ratio at $k' < k$. Repeating the manipulation will obtain

$$QOUT_t = \left[C_1\ QOUT_{t-1}\right] + \left[C_2\ QOUT_{t-2}\right] + \left[\sum_{j=0}^{k'} X_j''\,(TOUT_{t-j} - TZONER)\right],$$

where

C_1 = CR + CR',

C_2 = − CR * CR',

CR = <RFCOMR>, and

CR' = the common ratio of the X_j' series occurring at k'.

This process can be repeated indefinitely to obtain the shortest possible series. The coefficients in this series are usually called z-transfer factors.

The program does not explicitly use the modified response factors. It groups terms in a different way. Rather than precalculate X_j and Y_j, the quantities

$$SUMXDT_t = \sum_{j=1}^{k-1} X_j\,(TOUT_{t-j} - TZONER)$$

and

$$\text{SUMYDT}_t = \sum_{j=1}^{k-1} Y_j \; (\text{TOUT}_{t-j} - \text{TZONER})$$

are calculated and saved each hour.

$$\text{QOUT}_t = \left[\langle\text{RFCOMR}\rangle\ \text{QOUT}_{t-1}\right] + \left[X_0\ (\text{TOUT}_t - \text{TZONER})\right]$$

$$+ \sum_{j=1}^{k-1} \left[X_j\ (\text{TOUT}_{t-j} - \text{TZONER})\right] + \left[X_k\ (\text{TOUT}_{t-k} - \text{TZONER})\right]$$

$$- \left[\langle\text{RFCOMR}\rangle\ X_0\ (\text{TOUT}_{t-1} - \text{TZONER})\right] - \left[\langle\text{RFCOMR}\rangle \sum_{j=1}^{k-1} X_j\ (\text{TOUT}_{t-j-1}\right.$$

$$\left. - \text{TZONER})\right] = \left\{\langle\text{RFCOMR}\rangle\ [\text{QOUT}_{t-1} - X_0\ (\text{TOUT}_{t-1} - \text{TZONER})]\right\}$$

$$+ \left[X_0\ (\text{TOUT}_t - \text{TZONER})\right] + \text{SUMXDT}_t + \left[X_k\ (\text{TOUT}_{t-k} - \text{TZONER})\right]$$

$$- \left[\langle\text{RFCOMR}\rangle\ \text{SUMXDT}_{t-1}\right].$$

Instead of saving the previous hour's QOUT_t, the quantity $\text{XSXCMP}_t = \text{QOUT}_t - [X_0\ (\text{TOUT}_t - \text{TZONER})]$ is saved. Thus,

$$\text{QOUT}_t = \langle\text{RFCOMR}\rangle\ (\text{XSXCMP}_{t-1} - \text{SUMXDT}_{t-1})$$

$$+ \text{SUMXDT} + \left[X_0\ (\text{TOUT}_t - \text{TZONER})\right] + \left[X_k\ (\text{TOUT}_{t-k} - \text{TZONER})\right]$$

or

$$QOUT_t - X_0\,(TOUT_t - TZONER) = XSXCMP = \langle RFCOMR\rangle\,(XSXCMP_{t-1} - SUMXDT_{t-1})$$

$$+\; SUMXDT + X_k\,(TOUT_{t-k} - TZONER).$$

The above formula is used explicitly in the program to calculate XSXCMP. Then,

$$QOUT - X_0\,(TOUT_t - TZONER) = q_1 + q_2 - q_3 - X_0\,(TOUT_t - TZONER) = XSXCMP$$

is used to solve for $T = TOUT_t$:

$$[SOLI*\langle SURABSO\rangle] + [FILMU*(DBTR-T)] - [SKYA*MAX(GAMMA,0)]$$

$$- [X_0\,(T - TZONER)] = XSXCMP,$$

therefore,

$$T = \frac{-XSXCMP + [SOLI*\langle SURABSO\rangle] + [FILMU*DBTR] - [SKYA*MAX(GAMMA,0)] + [X_0*TZONER]}{FILMU + X_0}. \tag{III.31}$$

Here, q_1, q_2, and q_3 have the same definitions as in the section on quick walls (see Sec. III.2.6.1).

<u>Step 4</u>

Finally, to manipulate QIN_t in the same way as for $QOUT_t$, let

$$SUMYDT_t = \sum_{j=1}^{k-1} Y_j\,(TOUT_{t-j} - TZONER)$$

and

$$XSQCMP_t = QIN_t - Y_0\,(TOUT_{t-k} - TZONER) = \langle RFCOMR\rangle \left[XSQCMP_{t-1} - SUMYDT_{t-1}\right]$$

$$+\; SUMYDT + \left[Y_k\,(TOUT_{t-k} - TZONER)\right].$$

Then,

$$Q = QIN_t * XSAREA = \left[XSQCMP + Y_0 \, (TOUT_t - TZONER)\right] XSAREA.$$

Subdivision by subroutine

Step 1 is done in FILM.
Step 2 is done in WDTSUN.
Steps 3 and 4 are done in CALEXT.

Variable List:

Program Variable	Description	HOURLY-REPORT [VARIABLE-TYPE (VARIABLE-LIST number)]
T	Outside surface temperature (°R); also denoted $TOUT_t$.	E-W(6)
SOLI	Solar radiation incident on the surface from direct, diffuse, and reflected radiation (Btu/hr-ft^2).	E-W(1)
<SURABSO>	Surface absorptivity. This is the same as the keyword ABSORPTANCE in the CONSTRUCTION command.	-
FILMU	Combined radiative and convective outside surface conductance (Btu/hr-ft^2-°F).	E-W(3)
DBTR	Outside air temperature (°R).	GLOBAL(24)
GAMMA	Cosine of wall tilt.	-
X_0	zeroth X response factor.	-
X_j	jth X response factor.	-
Y_0	zeroth Y response factor.	-
Y_j	jth Y response factor.	-
TZONER	The constant space temperature (°R). This is the keyword TEMPERATURE in the SPACE command, converted from Fahrenheit to Rankine.	-
Q	Heat flow through the inside surface (Btu/hr).	E-W(5)
<RFCOMR>	The response factor common ratio.	

Program Variable	Description	HOURLY-REPORT [VARIABLE-TYPE (VARIABLE-LIST number)]
XSXCMP	Also called $XSXCMP_t$. The present hour's value of $QOUT_t - \left[X_0\,(TOUT_t - TZONER)\right] = \sum_{j=1}^{\infty} X_j\,(TOUT_j - TZONER)$.	E-W(13)
XSQCMP	Also called $XSQCMP_t$. The present hour's value of $QIN_t - \left[Y_0\,(TOUT_t - TZONER)\right] = \sum_{j=1}^{\infty} Y_j\,(TOUT_t - TZONER)$.	E-W(14)
QIN_t	Present (current) hour's heat flow through inside surface (Btu/hr-ft^2).	
$QOUT_t$	Present (current) hour's heat flow through outside surface (Btu/hr-ft^2).	
$TOUT_t$	Also called T. This hour's outside surface temperature (°R).	E-W(6)
TIN_t	This hour's inside surface temperature = TZONER (°R).	-
QIN_{t-j}, $QOUT_{t-j}$, $TOUT_{t-j}$	jth previous hour's value of QIN_t, $QOUT_t$, and $TOUT_t$.	-
SUMXDT	Also called $SUMXDT_t$. This hour's value of $\sum_{j=1}^{k} X_j\,(TOUT_{t-j} - TZONER)$.	E-W(10)
SUMYDT	Also called $SUMYDT_t$. This hour's value of	-

$$\sum_{j=1}^{k} Y_j \ (TOUT_{t-j} - TZONER).$$

k Defined by X_{k+1} = <RFCOMR> X_k.

XSAREA Surface area (ft^2).

2.6.3 Solar and Conduction Heat Gain Through Windows

The solar heat gain and conduction heat gain through windows are treated together, because they are interrelated. Solar heat gain is expressed by writing transmission and absorption coefficients as polynomials in the cosine of the solar incidence angle. Thus, the time-consuming, exact calculations do not have to be done every hour. For conduction heat gain, the windows are assumed to have no heat capacity; that is, they can be characterized by a U-value or resistance. The problem is complicated by the fact that the U-value of the window is primarily determined by the various film coefficients (i.e., by convective and radiative effects, not conductive effects), which depend on temperature and air movement. Thus, the U-value can vary widely, depending on the surrounding conditions. No attempt has been made to treat this problem exactly on an hourly basis. Instead, a conductance schedule can be input by the user to reflect the daily and seasonal changes in the window U-value.

Brief Description

1. The window U-value, exclusive of outside film resistance, is set to the user input U-value (keyword = GLASS-CONDUCTANCE in the GLASS-TYPE command) times the hourly value of the conductance schedule (input by keyword CONDUCT-SCHEDULE in the WINDOW command).

   UW = <GCON> * SV(IH),

   where UW is the window conductance for this hour, <GCON> is the glass conductance excluding the outside film coefficients and schedule multiplier, and SV(IH) is the hourly schedule value.

2. An air gap resistance, RA, is calculated for double and triple pane windows as

   UWI = 1/UW,

and

$$RA = C * UWI$$

where UWI is the inverse of UW before the outside film is added in and

$$\begin{aligned} C &= .586 \text{ for PANES} = 2, \\ &= .762 \text{ for PANES} = 2 \text{ and solar control film,} \\ &= .615 \text{ for PANES} = 3, \text{ and} \\ &= .718 \text{ for PANES} = 3 \text{ and solar control film.} \end{aligned}$$

3. The U-value is reset to the total U-value, including the outside film coefficient,

$$RO = \frac{1}{1.45 + (.302 * WNDSPD) + (.001661 * WNDSPD^2)}$$

and

$$UW = \frac{1}{RO + UWI},$$

where RO is the outside film resistance and WNDSPD is the wind speed (taken from the weather file).

4. A transmission coefficient for direct solar radition, TDIR, is calculated as a polynomial in the cosine of the solar incidence angle, ETA,

$$TDIR = <CAM1> + (<CAM2> * ETA) + (<CAM3> * ETA^2) + (<CAM4> * ETA^3).$$

The values of the constants <CAM1>, <CAM2>, <CAM3>, and <CAM4> depend on the glass-type, (<IGTYP>), and the number of panes, (<NPANE>). They are listed in Table III.5.

If TDIR < 0, set TDIR = 0.

5. The outside pane absorption coefficient, ADIRO, is calculated next. For windows with three panes, or with solar control film, the coefficient is expressed parametrically as a third order polynomial in ETA. For other windows, the form is A + (B * ETA) + [C/(D + ETA)].

For windows with solar control film (<IGTYP> $\geq$ 9), or with three panes (<NPANE> = 3),

TABLE III.5

COEFFICIENTS OF TRANSMISSION AND ABSORPTIONS BY GLASS-TYPE AND NUMBER OF PANES

<IGTYP>	<NPANE>	<CAM1>	<CAM2>	<CAM3>	<CAM4>	<CAM5>	<CAM6>	<CAM7>	<CAM8>	<CAM9>	<CAM10>	<CAM11>	<CAM12>	<CAM13>	<CAM14>	<CAM15>
1	1	-.01325	3.08716	-3.68232	1.48683	.077366	-.02718	-.002691	.040548	.79901	.05435	0.	0.	0.	0.	0.
2	1	-.01783	2.87789	-3.36746	1.34162	.152995	-.052962	-.007306	.052993	.75422	.10505	0.	0.	0.	0.	0.
3	1	-.02042	2.68177	-3.08269	1.21378	.226635	-.077564	-.013491	.064193	.71209	.15238	0.	0.	0.	0.	0.
4	1	-.0218	2.49833	-2.82369	1.10017	.295000	-.101216	-.021047	.074713	.67242	.27664	0.	0.	0.	0.	0.
5	1	-.02147	1.88493	-2.00686	.75829	.562829	-.185857	-.061251	.111426	.53535	.34727	0.	0.	0.	0.	0.
6	1	-.01805	1.42610	-1.43935	.53399	.790545	-.255091	-.110609	.141564	.42683	.46409	0.	0.	0.	0.	0.
7	1	-.01438	1.08159	-1.0387	.38277	.980573	-.308654	-.16173	.165985	.34063	.55547	0.	0.	0.	0.	0.
8	1	-.01743	.86343	-.83235	.32408	1.135704	-.34863	-.210036	.185579	.25535	.62726	0.	0.	0.	0.	0.
9	1	.00481	2.38471	-3.62354	1.74528	.07454	.72921	-1.16773	.57708	.48096	.20764	0.	0.	0.	0.	0.
10	1	.05900	1.42012	-2.78907	1.53279	.12275	1.13589	-1.80510	.90108	.22433	.33789	0.	0.	0.	0.	0.
11	1	.06022	.72969	-1.62806	.94241	.17780	1.37094	-2.39287	1.25713	.10961	.39818	0.	0.	0.	0.	0.
1	2	-.04674	2.17782	-1.72519	.34469	.091261	-.040933	-.002004	.025772	.67971	.05995	.092996	-.033680	-.020773	.229061	.04497
2	2	-.04689	2.01489	-1.52396	.2689	.176234	-.075101	-.005981	.037488	.64125	.11507	.095328	-.034882	-.025446	.270299	.04246
3	2	-.04587	1.86486	-1.34895	.20736	.256012	-.104796	-.011477	.047935	.60516	.16586	.096921	-.03588	-.029894	.310028	.03994
4	2	-.04429	1.72743	-1.19712	.15785	.331195	.130955	-.018186	.057561	.57125	.21283	.096889	-.035838	.033181	.342846	.0377
5	2	-.03616	1.28133	-.75498	.03613	.594925	-.213098	-.053708	.091548	.45447	.36902	.089692	-.031983	-.040842	.453595	.02986
6	2	-.029	.96842	-.5078	0.	.811113	-.272071	-.097404	.120594	.36233	.48657	.076972	-.025853	-.041299	.534024	.02371
7	2	-.0218	.7209	-.30812	-.03797	.989201	-.315959	-.143964	.145621	.28922	.57645	.061591	.0191	-.035739	.577135	.01887
8	2	-.01667	.54362	-.19377	-.04389	1.13449	-.348191	-.189376	.166789	.23107	.64588	.04728	-.013172	-.028599	.601909	.01504
9	2	-.06080	2.05564	-2.69305	1.14734	.09884	.75558	-1.32317	.69183	.42204	.21771	.00345	.15310	-.25557	.12470	.02761
10	2	-.02828	1.39759	-2.36614	1.19202	.16533	1.08038	-1.86788	.98539	.19718	.34580	.00396	.09226	-.18584	.10101	.01295
11	2	-.01087	.80978	-1.49973	.79181	.22139	1.28298	-2.389991	1.30397	.09584	.40334	.00317	.05022	-.11111	.06313	.00635
1	3	-.07946	1.83235	-1.14089	.06245	.05250	.21438	-.47980	.27048	.59665	.06371	.01319	.40254	-.60366	.27353	.08913
2	3	-.07744	1.87534	-.94910	-.00849	.07899	.49356	-1.02050	.55941	.56151	.12155	.00720	.38614	-.56201	.24980	.08354
3	3	-.07398	1.53391	-.79053	-.06125	.09430	.76996	-1.52161	.81901	.52886	.17440	.00387	.36318	-.51503	.22491	.07843
4	3	-.07000	1.40699	-.65924	-.10002	.10351	1.02874	-1.96850	1.04472	.49837	.22297	.00182	.33911	-.46993	.20197	.07371
5	3	-.05415	1.01319	-.31638	-.17111	.11447	1.85189	-3.26761	1.66806	.39468	.38249	-.00125	.25368	-.32667	.13354	.05794
6	3	-.04096	.73893	-.13535	-.17830	.11163	2.41186	-4.04142	2.00882	.31266	.50236	-.00172	.18902	-.22976	.09065	.04566
7	3	-.03111	.54938	-.03963	-.16309	.10627	2.78000	-4.49043	2.18911	.25008	.59003	-.00158	.14280	-.16541	.06365	.03638
8	3	-.02349	.40852	.01391	-.14056	.10087	3.03966	-4.76986	2.28996	.19958	.65837	-.00130	.10774	-.11924	.04506	.02893
9	3	-.07677	1.70143	-1.92190	.69420	.10263	.81050	-1.45692	.77444	.37425	.22428	.00382	.31536	-.52174	.25336	.05453
10	3	-.04924	1.19876	-1.83195	.85467	.17181	1.12770	-2.00978	1.07976	.17583	.35062	.00402	.19404	-.37657	.20115	.02555
11	3	-.02715	.70664	-1.18711	.58750	.22785	1.31646	-2.50434	1.38236	.08539	.40627	.00329	.10857	-.22740	.12628	.01248

ADIRO = <CAM5> + (<CAM6> * ETA) + (<CAM7> * ETA^{2}) + (<CAM8> * ETA^{3}).

For other windows (<IGTYP> < 9 and <NPANE> ≤ 2),

ADIRO = <CAM5> + (<CAM6> * ETA) + [<CAM7>/(<CAM8> + ETA)].

If ADIRO < 0, set ADIRO = 0.

6. The diffuse transmission coefficient, TDIF, is set

TDIF = <CAM9>.

7. The diffuse outside absorption coefficient, ADIFO, is set

ADIFO = <CAM10>.

8. Next, the inside pane absorption coefficients (ADIRI for direct radiation and ADIFI for diffuse radiation) are calculated.

If <IGTYP> < 9 and <NPANE> < 3, then

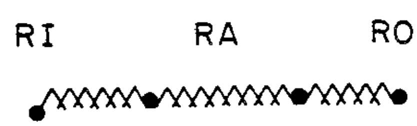
ADIRI = <CAM11> + (<CAM12> * ETA) + [<CAM13>/(<CAM14> + ETA)].

If <IGTYP> ≥ 9 or <NPANE> = 3, then

ADIRI = <CAM11> + (<CAM12> * ETA) + (<CAM13> * ETA^{2}) + (<CAM14> * ETA^{3}).

For single pane windows, ADIRI = ADIFI = 0.

9. For the absorbed radiation, it is necessary to estimate the amount of energy flowing into the room. The window is modeled as three resistances



where RI is the combined inside film resistance, RA is the air gap resistance, and RO is the combined outside film resistance. Then, the inward flowing fraction of the radiation absorbed on the inner pane, FI, is

FI = (RO + RA) * UW,

where

UW = 1/(RO + RA + RI),

and the inward flowing fraction of the radiation absorbed on the outer pane, FO, is

FO = RO * UW.

10. The radiation transmitted through the window, QTRANS (in Btu/hr-ft^2), is

QTRANS = (QDIF * TDIF) + (QDIR * TDIR),

where

QDIF = the amount of diffuse radiation striking the window in (Btu/hr-ft^2), and

QDIR = the amount of direct solar radiation striking the window in (Btu/hr-ft^2).

The amount of energy absorbed in the window and then flowing into the space, QABS (in Btu/hr-ft^2), is

QABS = QDIF(FO*ADIFO + FI*ADIFI) + QDIR(FO*ADIRO + FI*ADIRI).

11. The total amount of energy transmitted, QSOLG, and the total amount of energy absorbed and then flowing inward, QABSG, adjusted for window area, shading coefficient, and shading schedule, is

QSOLG = QTRANS * <WIAREA> * <GSHACO> * SV(IH)

and

QABSG = QABS * <WIAREA> * <GSHACO> * SV(IH),

where <WIAREA> is the window area and <GSHACO> is the shading coefficient.

12. The amount of heat entering the space through the window by conduction, QCON, is

$$QCON = [UW * (DBTR - TZONER) * <WIAREA>] + QABSG,$$

where DBTR is the dry-bulb temperature and TZONER is the space temperature.

Details and Derivation

Step 1

The user should be careful to select a value for <GCON> that includes the conductance of the bare window and the combined inside air film, but excludes the outside film coefficient. The user can use the conductance schedule to allow for the effects of blinds or shutters (in conjunction with the shading schedule), or for the seasonal variation of the outside temperature. The default values for <GCON> [in Btu/hr-ft^2-°F)] are

<GCON> = 1.47 for single pane,

= .574 for double pane, normal or heat absorbing glass (<IGTYP> $\leq$ 8),

= .305 for triple pane, normal or heat absorbing glass,

= .311 for double pane with reflective film (<IGTYP> > 8), and

= .232 for triple pane with reflective film.

These values were calculated (Ref. 15) assuming the emissivity of normal glass = .84, emissivity of the reflective coating = .05, gap thickness = 1/2 inch, inside temperature = 70°F, outside temperature = 32°F, wind speed = 15 mph. These conditions are winter conditions. For summer conditions, conductances would be slightly different because of the higher outside temperature.

Step 2

The values of the constant, C, were obtained for the same conditions listed above. The resistances and conductances of the layers for each type of window are shown in Table III.6.

For triple pane windows, C is calculated using RA = R_{gap2} + 1/2 R_{gap1}, because this gives a better result for QABS than just RA = R_{gap2}. The formula RA = C * UWI will only give the correct RA for the four cases shown in Table III.6; i.e., for the default UW's. When UW is altered from the default values, RA will not be correct. It should be accurate enough for most cases, however, because it is only used in the calculation of QABS, which is not normally a major component of the solar heat gain.

Step 3

The formula for outside film resistance is the same as that used for walls when ROUGHNESS = 6.

Step 4

The coefficients used in the approximate calculation of transmission and absorption coefficients are ultimately derived from fits of the approximate formulation to the exact calculation. For <IGTYP> ≤ 8, and <NPANE> = 2, the coefficients used here were obtained by a fit to a previous parameterization given in Ref. 16 and 2. For <IGTYP> > 8 or <NPANE> = 3, a new fit was made to the exact formulation using the computer programs documented in Ref. 15.

TABLE III.6

DEFAULT RESISTANCES AND CONDUCTANCES OF DOUBLE AND TRIPLE PANE WINDOWS

double pane, no reflective coating

	Inside	Gap	Outside	Total
resistance	.721484	1.02083	.22698	1.96929
conductance	1.38603	.979596	4.40567	.507796

double pane, with reflective coating

	Inside	Gap	Outside	Total
resistance	.763777	2.45361	.22698	3.44437
conductance	1.30928	.407562	4.40567	.290329

triple pane, no reflective coating

	Inside	Gap 1	Gap 2	Outside	Total
resistance	.765865	.993548	1.52097	.22698	3.50736
conductance	1.30571	1.00649	.657476	4.40567	.285115

triple pane, with reflective coating

	Inside	Gap 1	Gap 2	Outside	Total
resistance	.717987	.996004	2.59492	.22698	4.53589
conductance	1.39278	1.00401	.385369	4.40567	.220464

Steps 5 through 8

For <IGTYP> $\leq$ 8 and <NPANE> $\leq$ 2, the coefficients used in the parameterization of the absorption coefficients were obtained by a fit to a previous parameterization given in Refs. 16 and 2. For <IGTYP> > 8 or <NPANE> = 3, new fits were made using the algorithms in Ref. 15. The diffuse coefficients are always obtained by integrating the formulae for the direct transmission and absorption coefficients over one half of the total solid angle.

Steps 9 through 12

These steps are self-explanatory. Note that in Step 12, the absorbed radiation is included in the conductive heat gain.

Subdivision by Subroutine

All steps are performed in subroutine CALEXT.

Variable List:

Program Variable	Description	HOURLY-REPORT [VARIABLE-TYPE (VARIABLE-LIST number)]
UW	Window conductance for this hour Btu/hr-ft^2-°F.	WINDOW(1)
<GCON>	Window conductance excluding outside film coefficients and any schedule multiplier. This is the value input for the GLASS-CONDUCTANCE keyword in the GLASS-TYPE command.	-
SV(IH)	Used to denote an hourly schedule value.	-
UWI	Inverse of UW before outside film is added in.	-
RA	Air gap resistance.	-
RO	Outside film resistance.	-
<CAM1> - <CAM15>	Coefficients used in the calculation of the transmission and absorption properties of the window.	-
ETA	The cosine of the solar angle of incidence on the window.	E-W(15)
TDIR	The transmission coefficient for direct solar radiation.	WINDOW(2)
ADIRO	The outside pane absorption coefficient for direct solar radiation.	WINDOW(3)

Program Variable	Description	HOURLY-REPORT [VARIABLE-TYPE (VARIABLE-LIST number)]
TDIF	The diffuse solar transmission coefficient.	-
ADIFO	Outside diffuse solar absorption coefficient.	-
ADIRI	The inside pane direct solar absorption coefficient.	WINDOW(6)
ADIFI	The inside pane diffuse solar absorption coefficient.	-
FI	The inward flowing fraction of the solar radiation absorbed on the inside pane.	WINDOW(8)
FO	The inward flowing fraction of the solar radiation absorbed on the outside pane.	WINDOW(9)
QDIF	Amount of diffuse radiation striking the window per unit area (Btu/hr-ft^2).	WINDOW(12)
DQIR	Amount of direct radiation striking the window per unit area (Btu/hr-ft^2).	WINDOW(11)
QTRANS	Amount of solar radiation transmitted through the window per unit area (Btu/hr-ft^2).	WINDOW(13)
QABS	Amount of absorbed solar radiation entering through the window per unit area (Btu/hr-ft^2).	WINDOW(14)
QSOLG	Heat gain through window by solar radiation (Btu/hr-ft^2).	WINDOW(15)
<WIAREA>	Window area (ft^2).	-
<GSHACO>	Shading coefficient. This is the value input for the keyword SHADING-COEF in the GLASS-TYPE command.	-
QABSG	Heat gain through the window by radiation absorbed in the window and flowing inward (Btu/hr).	-
DBTR	Dry-bulb temperature (°R).	-
TZONER	Space temperature (°R). This is the value input for the keyword TEMPERATURE in the SPACE or SPACE-CONDITIONS instructions, converted from Fahrenheit to Rankin.	-
QCON	Window conduction heat gain, including QABSG (Btu/hr).	WINDOW(17)

2.7. Solar Incident On Surfaces

This algorithm accepts, as input, the direct normal solar radiation and the diffuse solar radiation from both the sky and the ground, and then calculates how much solar radiation falls onto a wall, door, or window.

Brief Description

The following steps are done for each exterior wall, each hour:

1. The diffuse radiation reflected from the ground, BG, is calculated

$$BG = \langle GNNREF \rangle \, [BSCC + RDNCC * RAYCOS(3)].$$

where <GNNREF> is ground reflectance, BSCC is the diffuse solar radiation from the sky on a horizontal surface and RAYCOS(3) is a solar direction cosine as explained in Sec. III.2.6.3.

2. The cosine of the incidence angle of the sun with the wall, ETA, is

$$ETA = [RAYCOS(1) * SIN(WA) + RAYCOS(2) * COS(WA)] \, SIN(WT) + RAYCOS(3) * COS(WT), \qquad (III.32)$$

where RAYCOS(1) and RAYCOS(2) are also solar direction cosines as explained in Sec. III.2.6.3, WA is the wall azimuth angle, and WT is the wall tilt angle.

3. The direct radiation per unit area on the wall, RDIR, is then

$$RDIR = RDNCC * ETA,$$

where RDNCC is the direct normal solar radiation per unit area.

4. The diffuse solar radiation incident on the wall is calculated next. If the user has input the sky and ground form factors, by inputting values for the keywords SKY-FORM-FACTOR and GND-FORM-FACTOR in the EXTERIOR-WALL command, the form factors (FFS and FFG respectively) are set to those values

$$FFS = \langle EWSKYFF \rangle$$

and

$$FFG = \langle EWGNDFF \rangle.$$

Otherwise, default values are calculated

if $WT < 45$, $FFS = 1$ and $FFG = 0$,

if $WT > 135$, $FFS = 0$ and $FFG = 1$, and

if $45 \leq WT \leq 135$, $FFS = 0.55 + (0.437 * ETA) + (0.313 * ETA^2)$ and

$$FFG = [1.0 - COS(WT)]\ 0.5. \tag{III.33}$$

Then,

$$RDIF = (FFS * BSCC) + (FFG * BG).$$

5. The total solar energy on the wall without the effects of shading, RTOT, is then

$$RTOT = RDIR + RDIF,$$

where RDIF is the diffuse solar radiation on the wall.

6. The total solar on the wall including the effects of shading, SOLI, is

$$SOLI = RTOT - (RDIR * XGOLGE),$$

where XGOLGE is the fraction of the wall that is shaded this hour.

7. For each wall, the solar energy incident on every door in the wall is calculated. If the user has input values for the keywords SKY-FORM-FACTOR and GND-FORM-FACTOR in the DOOR command, the diffuse radiation, DDIF, is calculated as

$$DDIF = (BSCC * \langle DRSKYFF\rangle) + (BG * \langle DRGNDFF\rangle),$$

where <DRSKYFF> and <DRGNDFF> are respectively the SKY-FORM-FACTOR and the GND-FORM-FACTOR for the door. If the user has not input values for SKY-FORM-FACTOR and GND-FORM-FACTOR for the door, DDIF = RDIF. This is without the effects of shading.

The total solar radiation on the door including the effects of shading is then

SOLID = DDIF + RDIR (1 - DRGOLGE),

where DRGOLGE is the fraction of the door that is shaded this hour.

8. For every window in the wall, the diffuse and direct solar radiation incident on the window are calculated. If the user has input values for the keywords SKY-FORM-FACTOR and GND-FORM-FACTOR in the WINDOW instruction, the diffuse radiation on the window, QDIF, is calculated as

   QDIF = (BSCC * <WISKYFF>) + (BG * <WIGNDFF>),

   where <WISKYFF> and <WIGNDFF> are respectively the SKY-FORM-FACTOR and GND-FORM-FACTOR for the window. If the user has not input values for SKY-FORM-FACTOR and GND-FORM-FACTOR for the window, QDIF = RDIF. This is without the effects of shading.

   The direct solar radiation on the window including the effects of shading, QDIR, is

   QDIR = (1 - AGOLGE) RDIR,

   where AGOLGE is the fraction of the window that is shaded this hour.

Details and Derivation.

Step 1

Self-explanatory.

Step 2

The direction cosines of the wall outward pointing normal are

C1 = sin(WT) sin(WA),
C2 = sin(WT) cos(WA), and
C3 = cos(WT).

Taking the dot product of this with the vector defined by the solar direction cosines, gives Eq. (III.32).

Step 3

Self-explanatory.

Step 4

The program user can input sky and ground form factors, or allow the program to calculate these values. If the user inputs no form factors for his building, the amount of diffuse solar energy entering the building will, in general, be overestimated. This is because most buildings are surrounded by trees, hills, and other buildings that increase the ground form factor above its default value of 0.5 (for vertical surfaces) and reduce the sky form factor by a corresponding amount. In most cases, and particularly for envelope-dominated buildings, the user should take the effort to input form factors by hand. The values that should be input are simply the fraction of the hemisphere, facing the building surface, that is covered by ground, buildings, or trees for the ground form factor, and the fraction of the hemisphere subtended by the sky, for the sky form factor. The default calculations done by the program are self-explanatory, except for Eq. (III.33). This is a parameterization of a curve through experimental points shown on page 301 of Ref. 5. Equation (III.33) establishes a directional dependence for diffuse light from the sky. Actually, for tilt angles between 45° and 135°, the factor calculated here is not strictly a form factor; it includes both form factor and anisotropic diffuse radiation effects. However, note that if the user specifies the sky and ground form factors, this anisotropic diffuse radiation model is bypassed.

Step 5

Self-explanatory.

Step 6

Note that shading applies only to direct solar radiation. Any blocking of diffuse light must be handled through the form factors.

Steps 7 and 8

Self-explanatory.

Breakdown by Subroutine

Steps 1 through 5 are done in SUN3.
Steps 6 through 8 are done in CALEXT.

Variable List:

Program Variable	Description	HOURLY-REPORT [VARIABLE-TYPE (VARIABLE-LIST number)]
BG	Intensity of solar radiation reflected from the ground and striking the wall (Btu/hr-ft^2).	E-W(16)
<GNDREF>	Ground reflectivity. This is the value input for the keyword GND-REFLECTANCE in the EXTERIOR-WALL command.	-
BSCC	Diffuse solar radiation from the sky on a horizontal surface (Btu/hr-ft^2).	GLOBAL(22)

Program Variable	Description	HOURLY-REPORT [VARIABLE-TYPE (VARIABLE-LIST number)]
RDNCC	Direct normal solar radiation (Btu/hr-ft^2).	GLOBAL(21)
RAYCOS(1) RAYCOS(2) RAYCOS(3)	Solar direction cosines.	GLOBAL(33-35)
WA	Wall azimuth angle (in the building coordinate system).	-
WT	Wall tilt angle (in the building coordinate system).	-
ETA	Cosine of the solar angle of incidence.	E-W(15)
RDIR	Intensity of direct solar radiation striking the wall, shading neglected (Btu/hr-ft^2).	E-W(17)
FFG	Default ground form factor.	-
FFS	Default sky form factor.	-
<EWGNDFF>	Ground form factor for the exterior wall, as input via the keyword GND-FORM-FACTOR in the EXTERIOR-WALL command.	-
<EWSKYFF>	Sky form factor for the exterior wall, as input via the keyword SKY-FORM-FACTOR in the EXTERIOR-WALL command.	-
RDIF	Intensity of diffuse solar radiation striking the wall (Btu/hr-ft^2).	E-W(18)
RTOT	Intensity of total solar radiation striking the wall, shading neglected (Btu/hr-ft^2).	E-W(19)
SOLI	Intensity of total solar radiation striking the wall with shading taken into account (Btu/hr-ft^2).	E-W(1)
XGOLGE	Fraction of the wall that is shaded this hour.	E-W(2)
DDIF	Intensity of the diffuse solar radiation striking the door (Btu/hr-ft^2).	-
<DRGNDFF>	Ground form factor for the door, as input via the keyword GND-FORM-FACTOR in the DOOR command.	-

Program Variable	Description	HOURLY-REPORT [VARIABLE-TYPE (VARIABLE-LIST number)]
<DRSKYFF>	Sky form factor for the door, as input via the keyword SKY-FORM-FACTOR in the DOOR command.	-
SOLID	Intensity of solar energy striking the door with shading taken into account (Btu/hr-ft^2).	DOOR(3)
DRGOLGE	Fraction of the door that is shaded this hour.	DOOR(2)
QDIF	Intensity of diffuse solar radiation striking the window (Btu/hr-ft^2).	WINDOW(12)
<WISKYFF>	Sky form factor for the window, as input via the keyword SKY-FORM-FACTOR in the WINDOW command.	-
<WIGNDFF>	Ground form factor for the window, as input via the keyword GND-FORM-FACTOR in the WINDOW command.	-
QDIR	Intensity of direct solar radiation striking the window with shading taken into account (Btu/hr-ft^2).	WINDOW(11)
AGOLGE	Fraction of the window that is shaded this hour.	WINDOW(10)

2.8 Infiltration

Infiltration is one of the largest components contributing to heating loads. Unfortunately, it is also the component that is the most difficult to model accurately. The difficulty primarily arises from lack of information about the building's construction, it's surroundings, and local weather variables. Accurate modeling of airflow into and within a building requires knowledge of the pressure difference across the building envelope. This requires knowledge of the dry-bulb temperature, wind speed, and wind direction at the building's location. Wind speed and wind direction in particular will have little correlation with the same quantities measured at the local weather station because of effects of the local terrain and the surrounding buildings. Accurate modeling of infiltration also requires knowledge of the air tightness of the building envelope and the resistance to air flow between spaces and floors within the building. Such information is usually not available. Thus, infiltration in building energy analysis programs is usually treated by very simple, approximate models. DOE-2 employs three different models: air-change, crack method, and residential (Achenbach-Coblentz). Each will be described separately below.

2.8.1 Air-Change Method.

Outline

CFMINF = (.001922 * WNDSPD * <ZACHG> * <ZVOL>) + (<ZCFMSF> * <ZFLRAR>)

(III.34)

where

CFMINF is the infiltration in CFM,

WNDSPD is the wind speed in knots,

<ZACHG> is the air-changes per hour input by the user via the AIR-CHANGES/HR keyword in the SPACE or SPACE-CONDITIONS instruction,

<ZVOL> is the volume of the space input by the VOLUME (or HEIGHT, WIDTH, and DEPTH) keyword in the SPACE instruction,

<ZCFMSF> is the CFM per square foot input by the INF-CFM/SQFT keyword in the SPACE or SPACE-CONDITIONS instruction,

<ZFLRAR> is the area of the space input by the AREA (or WIDTH and DEPTH) keyword in the SPACE instruction.

Details and Derivation

The user has a choice between using the keywords INF-CFM/SQFT and AIR-CHANGES/HR. If he uses INF-CFM/SQFT, he will get the value he has input times the floor area, with no correction for wind speed. If he uses AIR-CHANGES/HR, a linear wind speed correction is made. He will get the value he input when the wind speed is 10 mph. The constant in Eq. (III.34) is

$$.001922 = \frac{1}{60 \text{ minutes/hour}} * \frac{1}{10 \text{ mph}} * 1.153 \text{ mph/knot.}$$

Infiltration is proportional to $(\Delta p)^n$, where Δp is the inside-outside pressure difference and n can have values from 0.5 to 0.9, depending on the type of construction [see Ref. 1, p. 21.4, Eq. (4)]. Because Δp is proportional to the wind speed squared, the infiltration cfm will be proportional to wind speed raised to a power between 1 and 1.8. Thus, a linear wind speed adjustment is reasonable, but it is not the only functional form that could have been chosen.

2.8.2 Residential Method

Outline

$$AC = A + (B * WNDSPD) + (C * |TZONER - DBTR|) \qquad \text{(III.35)}$$

CFMINF = AC * <ZVOL>/60

where

AC is the number of air changes per hour,

TZONER is the space temperature in °R. The user has input this in °F by the keyword TEMPERATURE in the SPACE or SPACE-CONDITIONS instruction,

DBTR is the outside dry-bulb temperature in °R,

A is the first value from the keyword RES-INF-COEF in the SPACE or SPACE-CONDITIONS instruction,

B is the second value from RES-INF-COEF, and

C is the third value from RES-INF-COEF.

Details and Derivation

Equation (III.35) has no theoretical justification, but it is a form that fits a wide range of residential infiltration data fairly well (Refs. 17, 18, and 19). The default values for A, B, and C are

A = .252
B = .0251
C = .0084.

These values were developed by Steve Petersen of NBS (Ref. 20). When used in Eq. (III.35), they yield one air-change per hour at the winter design condition of 50°F temperature difference and 15 mph wind speed. This corresponds to the value measured at the Bowman house on the NBS campus. A yearly average for Eq. (III.35), using the default coefficients, and averaged over US climates, gives 0.6 air-changes per hour, which matches the mean of 50 experiments on infiltration (Refs. 20 and 21). It is recommended that the residential infiltration method be applied only to residences, not to larger commercial buildings.

2.8.3 Crack Method

Outline

1. For each exterior wall in each space

$$PTWV = |.000638 * WNDSPD^2 * COS(SDELTA)| \qquad (III.36)$$

where

SDELTA is the angle between the surface outward normal and the wind direction. If $|SDELTA| > \pi/2$, SDELTA is set to $\pi/2$ so that PTWV = 0 for wind coming from behind the wall, and

PTWV is pressure, in inches of H_2O, caused by the wind velocity.

2. For each space

$$PSE = .255 * PATM * \left[\frac{1}{DBTR} - \frac{1}{TZONER}\right] <ZHTNEU> \qquad (III.37)$$

where

PATM is the atmospheric pressure in inches of Hg,

<ZHTNEU> is the vertical distance from the neutral pressure level in feet. This is input via the NEUTRAL-ZONE-HT keyword in the SPACE or SPACE-CONDITIONS instruction, and

PSE is the pressure, in inches of H_2O, caused by the stack effect.

3. For each exterior wall, window, or door

$$PCO = PTWV + PSE \qquad (III.38)$$

and

$$CFMINF = C * PCO^n * A \qquad (III.39)$$

where

C is the infiltration coefficient (keyword INF-COEF in the EXTERIOR-WALL, WINDOW or DOOR instruction),

A is the area in ft^2 for delayed walls; for windows, doors, and quick walls, A is the perimeter in feet, and

n is .8 for delayed walls, .5 for doors and quick walls, and .66 for windows.

CFMINF is then summed over all windows, doors, and exterior walls to obtain the cfm for the whole space.

Details and Derivation

1. Equation (III.36) is derived from the expression for kinetic energy. The constant is

$$.000638 = [1/2]\left[.075\ \frac{\text{lbs of air}}{\text{ft}^3}\right] * \left[\frac{1}{32.17}\frac{\text{lbs force-sec}^2}{\text{lbs mass-ft}}\right] *$$

$$\left[.1922\ \frac{\text{inches } H_2O}{\text{psf}}\right] * \left[2.849\ \frac{(\text{ft/sec})^2}{\text{knots}^2}\right].$$

This is the same equation as Eq. (1), page 21.1, Ref. 1, with the units of wind speed changed from mph to knots.

2. Equation (III.37) can be derived from the ideal gas law

$$Pv = RT$$

where

P is the pressure in lbs/ft^2,
v is the specific volume in ft^3/lbs,
T is temperature in °R, and
R is the gas constant for air.

The constant in Eq. (III.37) is

$$\frac{1}{R}\left[13.5955\ \frac{\text{inches } H_2O}{\text{inches Hg}}\right] = \frac{13.5955}{53.34} = .255.$$

Equation (III.37) is the same as Eq. (2), page 21.2, Ref. 1, with the units of P changed from psi to inches of Hg.

The neutral pressure level of a building is located at 1/2 the building height if the openings causing the infiltration are of equal size and are equally distributed over the building height. Available data from tall buildings place the neutral pressure level anywhere from .3 to .7 of the building height.

3. In Eq. (III.38), PCO is the inside-outside pressure difference caused by wind and density gradient. The full value of PTWV from Eq. (III.36) and PSE from Eq. (III.37) are usually not used as pressure differences. Using PSE as a pressure difference neglects the pressure loss caused by resistance to flow within the building. Actual values from measurement range from .63 to .82 of PSE. Using the full value of PTWV neglects the pressure buildup within the building. A value of .64 PTWV is recommended to obtain the actual Δp. Thus, Eqs. (III.38) and (III.39) tend to overestimate the infiltration and the infiltration coefficients should be lowered accordingly.

   Equation (III.38) is Eq. (4), page 21.4, Ref. 1. Values for the infiltration coefficients can be obtained from Tables 2 and 3 and Figs. 5 and 10, Chapter 21, Ref. 1. The exponent used in Eq. (III.39) is derived from data as given in Ref. 1. Its value can easily be incorrect by ±.1 for any given case. Equation (III.39) can only give a very approximate idea of the actual infiltration.

Final Calculations for Reporting

The CFMINF calculated by LOADS is passed to the SYSTEMS program, where the latent load from infiltration is calculated. This cannot be done accurately in LOADS, because the inside temperature and humidity ratio are not known.

For reporting purposes, however, an estimate of both the sensible and latent loads from infiltration is made in LOADS. These quantitites are then displayed in reports LS-B, LS-C, LS-E, and LS-F. The hourly loads and the building peak loads reported in LOADS do contain the sensible infiltration load. The hourly values are later corrected, in subroutine TEMDEV in the SYSTEMS program, once the inside temperature and humidity ratio are known.

The sensible load is calculated from

QINFS = 14.4 * DENSIN * CFMINF * (DBTR - TZONER)

where

QINFS is the sensible load from infiltration in Btu/hr and
DENSIN is the density of the air inside the space.

The equation is Cp ρ ΔT, with Cp the specific heat of air and ρ the density of air. The constant 14.4 is

$$14.4 = 60 \text{ min/hr} * Cp = 60 * .24.$$

DENSIN is obtained from

$$\text{DENSIN} = \frac{\text{PATM}}{.754 * \text{TZONER}},$$

which is a truncation of the usual formula given in Ref. 2, page 163.

The latent load contribution is calculated from

$$\text{QINFL} = 63000 * \text{DENSIN} * \text{CFMINF} * (\text{HUMRAT} - \text{HRODA})$$

where

QINFL is the latent load from infiltration,
HUMRAT is outside humidity ratio in lbs H_2O/lb dry air, and
HRODA is the inside humidity ratio in lbs H_2O/lb dry air.

The equation calculates the heat released by precipitating out the excess moisture in the outside air to maintain the inside humidity ratio at HRODA.

The constant 63000 is

60 min/hr * (latent heat of fusion of H_2O).

For outside temperatures below 50°F, HRODA is set to HUMRAT, i.e., there is assumed to be no latent load. For outside temperatures above 50°F, HRODA is given by

$$\text{HRODA} = \frac{33.2 + .245(\text{DBTR} - 50)}{7000}.$$

This assumes that the dew point temperature of the air leaving the cooling coil is 50°F for 50°F outside air temperature and the dew point is 54°F for an outside air temperature of 90°F. Other values are then obtained by linear extrapolation.

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IV. SYSTEMS SIMULATOR

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1. SYSTEMS OVERVIEW
by James J. Hirsch

1.1 Overview of How the SYSTEMS Simulation Works

The SYSTEMS program simulates the distribution equipment that provides heating, ventilation, and/or air-conditioning to the thermal zones of a building. The SYSTEMS program also simulates the interaction of this equipment with the building loads. This simulation is composed of two major concepts:

1. Because the LOADS program calculated the "load" at a constant reference space air temperature, it is necessary to correct these calculations to account for equipment operation.

2. Once the net sensible heat exchange between the thermal zones and the HVAC equipment is solved, the complete heat and moisture exchange between equipment, heat exchangers, and the building can be calculated. Later, in the PLANT program, the resultant primary equipment or utility "loads" can be calculated.

The constant space air temperature calculation in LOADS has two major advantages. First, it greatly reduces the computational time in the LOADS program, although it introduces some approximations that preclude accurate calculation of certain configurations (see weighting factor section for details). Second, and more important, it allows tight coupling between the building loads calculations and the equipment calculations. This coupling is very important because the equipment operation, in response to zone temperature, is most often a nonlinear process. This results in energy input to the equipment that is not always proportional to the building "load". Stated another way, the operation of and energy input to the HVAC equipment quite often can mask the base building envelope load from LOADS.

The dynamics of the interaction between the HVAC equipment and the building, including its contents, are calculated by the simultaneous solution of the room air temperature weighting factors with the equipment controller action. To eliminate the necessity of solving the interactions of all the zones simultaneously, the zone temperatures from the previous hour(s) calculation are used to approximate the heat flow across internal walls. Likewise, to eliminate the necessity of iteration until all temperatures in the equipment loop converge, temperature histories are used in the calculation of equipment capacities. The equipment capacities are then used in calculating the relationship between the equipment output and the controller signal.

Once the supply air temperature and the thermal zone temperature are known, the return air temperature can be calculated. Also, at this point, the outside air system and other controls can be simulated. Then, the sensible heat exchange across all coils can be calculated.

The moisture content of the air is calculated at three points in the system: in the supply air stream, the return air stream, and the mixed air stream (mixed return air and outside air). These values are calculated by assuming a steady state solution of the system moisture balance. The calculated return air humidity ratio is used as the input to the controller that activates a humidifier in the supply air flow. Also, the return air humidity ratio is used to reset the cooling coil controller, in an attempt to prevent the exceeding of the specified maximum space humidities. The moisture condensation on cooling coils is simulated by characterizing the coils by their bypass factors and then solving the bypass relation simultaneously with the system moisture balance.

Once the above sequence is complete, all heating and cooling coil loads are known. These values are then either (1) passed on to the PLANT program as heating and cooling loads, or (2) used in the simulation of packaged HVAC units in the SYSTEMS program.

1.2 Room Air Temperature and Extraction Rate Calculation

As described in the weighting factor section of this manual, the net heat input to, or the net heat extraction from, a space is related to the air temperature through the room air transfer functions:

$$\sum_{n=0,2} P_n^j \, Qnet_{z-n}^j = \sum_{n=0,3} g_n^j \, \Delta T_{z-n}^j \tag{IV.1}$$

where

P_n^j, g_n^j are the transfer functions that relate the net heat extraction rate to a pulse in the room air temperature for room j at time z-n (n=0 is the current simulation hour);

$Qnet_{z-n}^j$ is the net heat extraction in response to the temperature deviation in space j at time z-n;

ΔT_{z-n}^j is the deviation in space j air temperature from the LOADS calculation temperature; and

$$\Delta T_{z-n}^j = T^{Loads,j} - T_{z-n}^j \tag{IV.2}$$

where

$T^{Loads,j}$ is the LOADS calculation temperature for space j, and

T_{z-n}^j is the air temperature for space j at time z-n.

Now, consider the details of the terms contained in $Qnet_{z-n}^j$, as is appears in Eq. (IV.1). It represents the deviation in heat input, between the SYSTEMS the SYSTEMS calculation and the LOADS calculation, caused by the air temperaature deviation. Thus, $Qnet_{z-n}^j$ must contain terms to correct the LOADS-calculated value for space temperature deviations. The main terms that are space temperature dependent are the infiltration, as well as external and internal surface heat transfer. The correction to the infiltration is proportional to the deviation of the space temperature (except where the infiltration flow rate is a function of space temperature, INF-METHOD = RESIDENTIAL). The correction for internal and external wall heat transfer is approximated, by using overall U-values.

$$Qnet^j_{z-n} = ER^j_{z-n} - Q^{Loads,j}_{z-n} - \left(1.08 * CINF^j_{z-n} * \Delta T^j_{z-n}\right) - \left(k_E * \Delta T^j_{z-n}\right)$$

$$- \sum_{k=1}^{nattach} \left[(UA)_k * (\Delta T^j_{z-n} - \Delta T^k_{z-n})\right] \qquad (IV.3)$$

where

ER^j_{z-n} is the equipment heat input to space j at the time z-n,

$Q^{Loads,j}_{z-n}$ is the "constant temperature" load from the LOADS program for space j at time z-n,

$CINF^j_{z-n}$ is the infiltration air flow rate to space j at time z-n,

k_E is the overall external wall thermal conductance,

$(UA)_k$ is the overall thermal conductance between space j and space k,

and

nattach is the number of spaces adjoining space j.

Note that the last term in Eq. (IV.3) only corrects for spaces j and k temperature deviations from their respective LOADS-calculated temperatures. The term $Q^{Loads,j}_{z-n}$ contains the net heat transfer caused by unequal LOADS-calculated temperatures for the spaces. It can be seen from this equation that a solution for one space temperature would require a simultaneous solution for all the space temperatures. To simplify this problem, the program substitutes z-n-1 for z-n in the space terms for the internal heat transfer. This is a good approximation if the derivative of the zone temperatures is roughly constant. By substituting Eq. (IV.3) into Eq. (IV.1), collecting terms, and solving for T^j_n

$$T^j_z = \frac{F - \left(P^j_o * ER^j_z\right)}{G_o} \qquad (IV.4)$$

where

$$F = \left(P_o^j * Q_z^{Loads,j}\right) + \sum_{n=1,3}\left(G_n^j * \Delta T_{z-n}^j\right) + \sum_{n=0,2}\sum_{k=1,nattach}\left[P_n(UA)_k * \Delta T_{z-n-1}^k\right],$$

$$G_n^j = g_n^j + \left[P_n^j * \left(k_T + 1.08 * CINF_{z-n}^j\right)\right], \text{ and}$$

$$k_T = k_E + \sum_{k=1,nattach} (UA)_k .$$

This is simplified when it is remembered that $P_0 = 1.0$ and $P_3 = 0$.

The equipment heat input $\left(ER_z^j\right)$ takes different forms, depending upon the type of zone and the type of equipment. The simplest case is for the unconditioned zone, where the value is zero. The next simplest case is for a return air plenum, where ER_z^j is calculated from the temperature of the air entering the plenum. The heat gain from the return air is expressed as

$$ER_z^j = 1.08 * CFM * \left[\frac{T_{z-1}^j + T_z^j}{2.0} - TR\right] \tag{IV.5}$$

where

CFM is the return air flow rate and
TR is the return air temperature entering the plenum.

Last, for equipment controlled by the zone thermostat action, a linear relationship is assumed to describe the interaction of the thermostat, space temperature, and equipment output. This relationship is graphically shown in Fig. IV.1. Algebraically,

$$ER_i^j = W^j + \left(S^j * T_z^j\right) \tag{IV.6}$$

where

W^j and S^j are the intercept and slope of this linear relationship.

It should be noted that the values of ER_i^j in Eq. (IV.6) are restricted to a certain range because of the capacity of the equipment. Thus, the equipment capacity must be estimated before the preceding equations can be solved. This capacity estimate is made by using the dry- and wet-bulb temperatures from the end of the previous time step (hour). Also, there are three distinct thermostatic regions of Eq. (IV.6) with different slopes and intercepts. These are the heating, dead band, and cooling regions of the thermostat. The minimum and maximum values, plus the resulting slope and intercept, for each of these regions must be calculated.

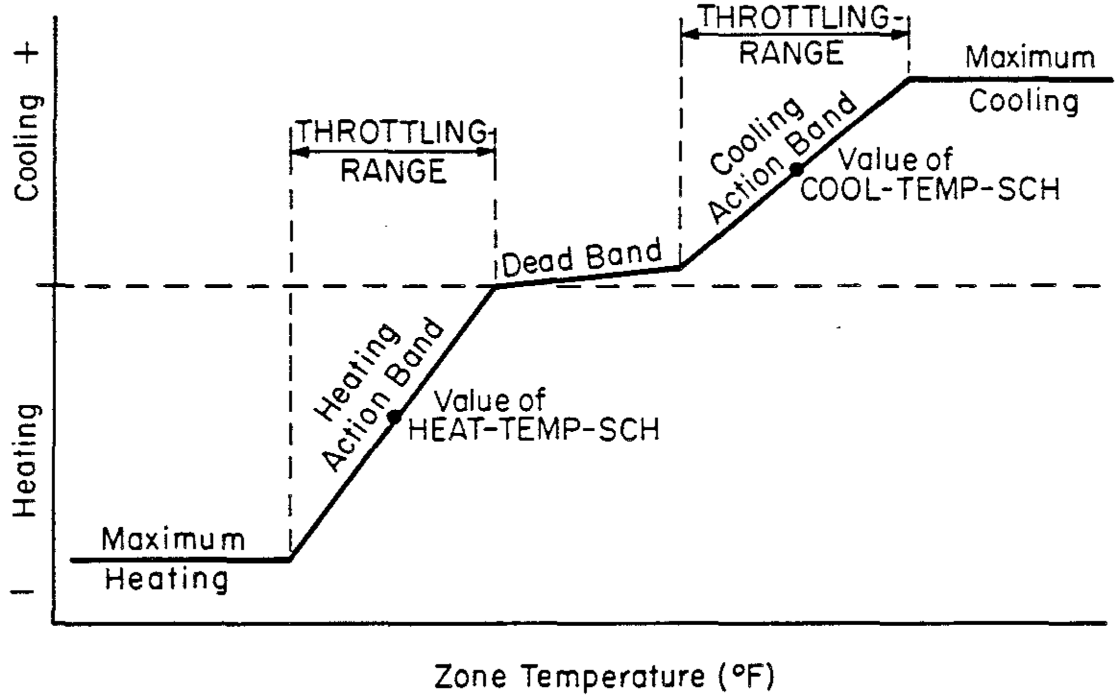

Fig. IV.1. Five possible regions of thermostatic action.

If the system being simulated is an air system, the supply air temperature is assumed to be constant during the hour. Thus, in addition to Eq. (IV.6), or an equation similar to Eq. (IV.5) is needed to describe the fluctuations in the extraction rate during the hour, caused by the fluctuation of space temperature relative to the supply air temperature.

It should be noted that the previous equations are somewhat complicated whenever the supply air temperature and/or the air flow rate are also expressed as a function of space temperature (as in discriminator control and variable air volume systems). In these cases, it is necessary to introduce more equations of the same form as Eq. (IV.6) and then find the equilibrium supply air temperature by iterating through the zones to find the average controller signals during this time step (hour).

1.3 Simulation of Heat and Moisture Exchange with HVAC Equipment

The first step to simulating equipment performance is to characterize the equipment in terms of its primary performance parameters. In most cases, this means it is necessary to know the variation of equipment capacity and energy consumption as a function of other parameters, such as humidity, part load ratio, etc. In this program, the designers have chosen to express both equipment capacity and energy input as the product of a "rated" value and modifier functions.

$$CAP_{T_1,T_2} = CAP_{rated} * f(T_1,T_2) \tag{IV.7}$$

Capacity, for example, is usually specified, in the manufacturer's literature, in terms of a rated value at certain conditions. Often this information is accompanied by off-rated values. As seen in Eq. (IV.7), it is assumed that the capacity at an off-rated point can be expressed as the product of the rated capacity and a function, which is normalized with respect to the rated capacity

$$f(T_{1,rated}, T_{2,rated}) = 1.0. \tag{IV.8}$$

Very often, more than two parameters are of importance to equipment operation. In this case, it is assumed that this can be well approximated by the product of multiple modifier functions

$$CAP_{T_1,T_2,T_3} = CAP_{rated} * f_1(T_1,T_2) * f_2(T_3). \tag{IV.9}$$

The program is capable of handling functions of one or two independent variables to produce linear, quadratic, cubic, bi-linear, and bi-quadratic curves (see Figs. IV.2 through IV.6).

For all modifier functions used in the program, there are built-in default performance curves that the user can easily replace (see the SYSTEM- EQUIPMENT subcommand in the SYSTEMS program and the CURVE-FIT instruction in BDL). The rated point values can be calculated by the program or the user may choose to specify them. Although the specification of default-overriding performance data is done in the SYSTEMS input, the calculation of the new performance curve is done in BDL. Those calculations are discussed in Chap. II of this manual.

For cooling equipment, it must be possible to calculate the capacity, both sensible and latent, and the energy input to handle the load. The sensible capacity, at a particular operating point, is calculated from three modifier functions. The first modifier function is used to calculate the total capacity and the second and third are used to modify the rated sensible capacity for off-rated conditions. Then, a check is made to insure that the sensible

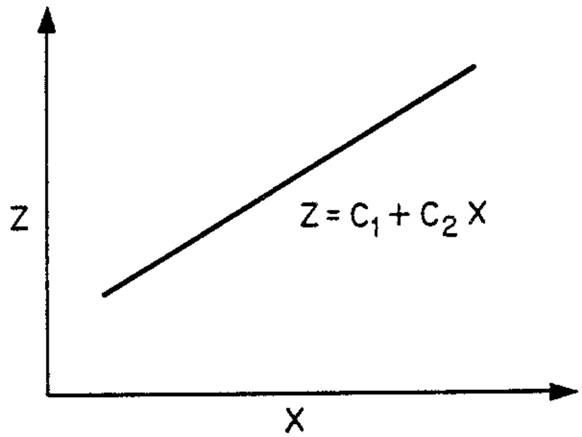

Fig. IV.2. Linear equation.

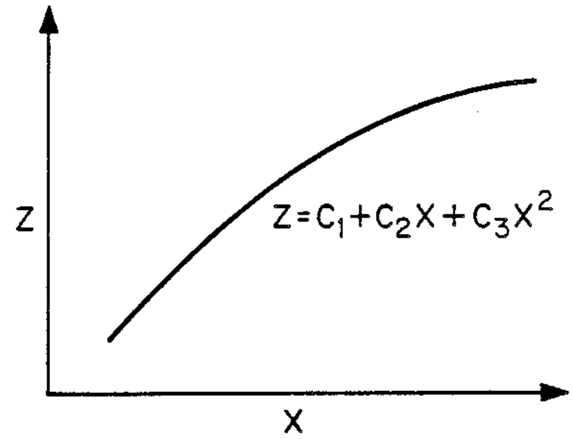

Fig. IV.3. Quadratic equation.

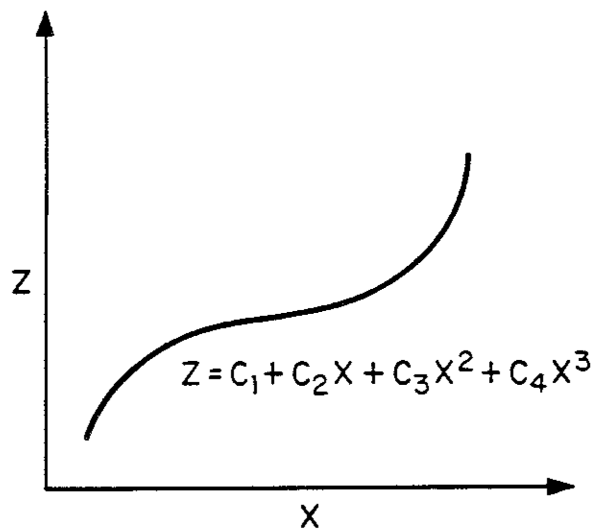

Fig. IV.4. Cubic equation.

cooling capacity does not exceed the total cooling capacity. In this way, an accurate transition from a wet to a dry coil surface condition is obtained. Because this transition is not a smooth one, multiple functions are needed to describe these regions

$$QCT_{T_1,T_2} = \text{COOLING-CAPACITY} * \text{COOL-CAP-FT}(T_1,T_2) \text{ and} \tag{IV.10}$$

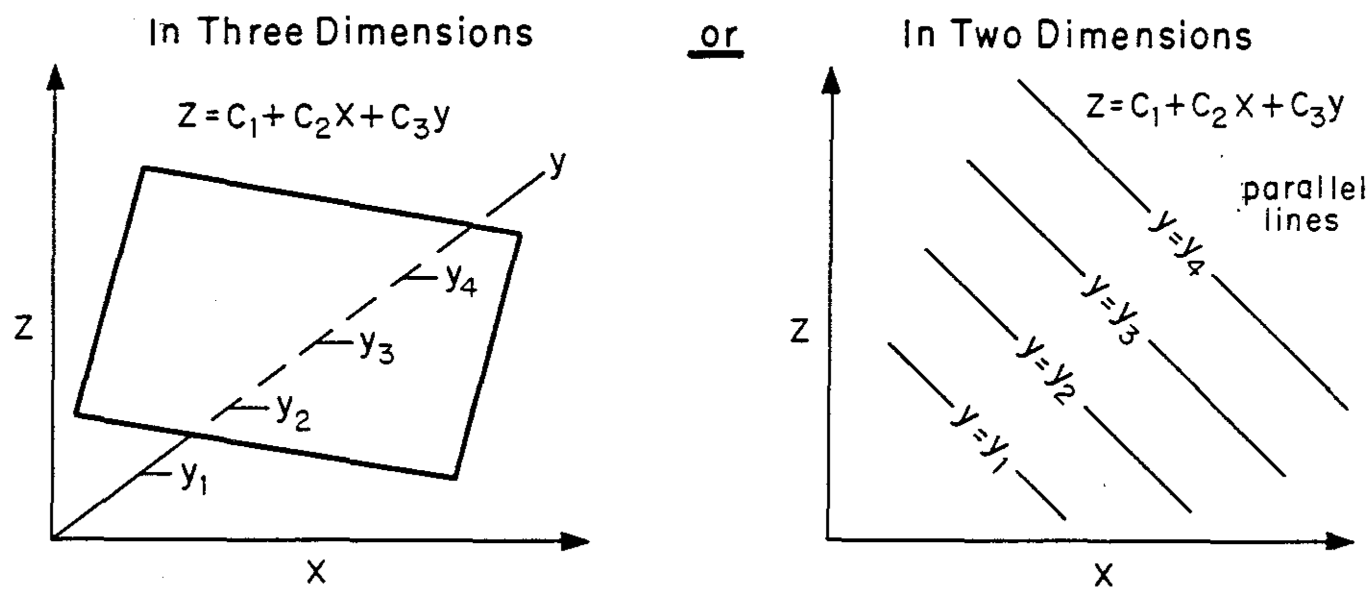

Fig. IV.5. Bi-linear equation.

$$QCS_{T_1,T_2,T_3} = \text{COOL-SH-CAP} * \text{COOL-SH-FT}(T_1,T_2) - f_{dx1}(T_3), \text{ or}$$

$$QCT_{T_1,T_2}, \text{ whichever is smaller.}$$

where

QCT = Total cooling capacity,

QCS = Sensible cooling capacity,

T_1 = wet-bulb temperature entering the evaporator,

T_2 = either the dry-bulb temperature of the air entering the evaporator for chilled water systems <u>or</u> the dry-bulb temperature of the air entering the condenser for direct expansion units,

T_3 = dry-bulb temperature of the air entering the evaporator for direct expansion units,

f_{dx1} = either 0.0 for chilled water systems, <u>or</u> 1.08 * CFM * (1.0 - COIL-BF) * (80.0 - T_3) for direct expansion units, where CFM is the air flow rate and COIL-BF is the coil bypass factor.

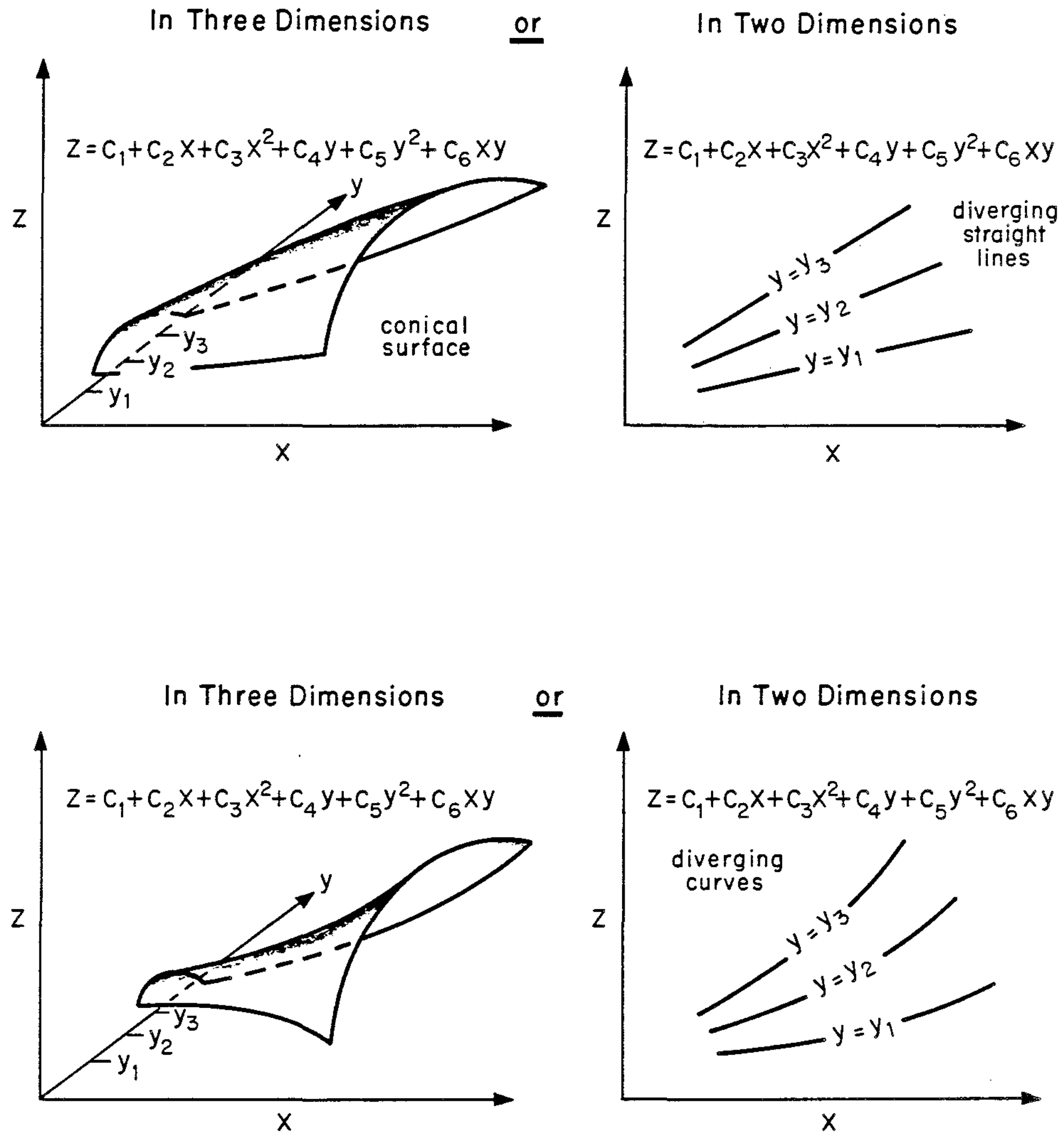

Fig. IV.6. Bi-quadratic equation.

From the above expressions, it can be seen that at full load the amount of latent load or moisture removal is known. Because the number of hours at full load operation are small and other factors that affect moisture condensation on the coil can vary, it was necessary to develop a slightly more complex method of calculating the latent load. Using only the expressions in Eq. (IV.10) would also make it necessary to iterate during a single time step in order to get the supply and mixed air moisture levels accurately. This is because of the fact that the supply and mixed air moisture levels are coupled. One way to avoid this problem would be to ignore it by using the previous hour's evaporator entering wet-bulb temperature to calculate the capacity and resultant supply air and new (for the next hour) mixed air wet-bulb temperature. These problems have been avoided by using an accurate, but simple, relationship that can be solved simultaneously with a system moisture balance to produce steady state values for the moisture levels at the important points in the system. Thus, the the coil bypass factor concept is introduced.

The coil bypass factor (CBF) model characterizes the air exiting the cooling coil as being composed of two major streams, that is, (1) the air that has not been influenced by the coil and (2) the air that leaves at the coil surface condition. The coil bypass factor is the fraction of air that exits unaffected by the coil. Thus, relationships have been established for the exit dry-bulb temperature and the exit humidity ratio, in terms of the entering conditions and the coil bypass factor. This relationship is graphically shown in Fig. IV.7. The exit dry-bulb temperature and the exit humidity ratio for a wet coil surface are

$$T_{exit} = (T_{entering} * CBF) - [(1.0 - CBF) * T_{surf}] \qquad (IV.11)$$

$$W_{exit} = (W_{entering} * CBF) - [(1.0 - CBF) * W_{surf},] \qquad (IV.12)$$

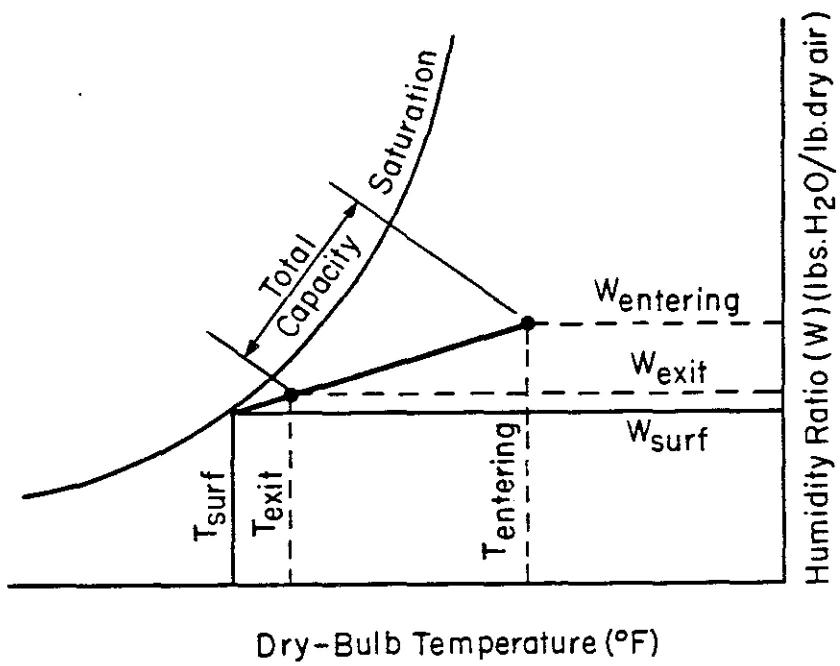

Fig. IV.7. Cooling coil performance.

where T_{surf} is the coil surface temperature and W_{surf} is the coil surface humidity ratio at saturation. For a dry coil surface, W_{exit} and $W_{entering}$ are equal.

The coil bypass factor is a function of both physical and operational parameters of the coil. Because the physical characteristics are constant, the coil bypass factor is expressed as a product of the design, or rated, value and two modifier functions. The most important variable is the coil surface air velocity, which is directly proportional to the unit flow rate, CFM. Of secondary importance are the entering coil wet-bulb and dry-bulb temperatures. The coil bypass factor is

$$CBF = COIL\text{-}BF * COIL\text{-}BF\text{-}FCFM(PLRCFM) * COIL\text{-}BF\text{-}FT(T_1,T_2) \tag{IV.13}$$

where

T_1 = wet-bulb temperature entering the evaporator,

T_2 = either the dry-bulb temperature of the air entering the evaporator for chilled water systems, or the dry-bulb temperature of the air entering the condenser for direct expansion systems, and

PLRCFM = ratio of instantaneous flow rate to rated flow rate.

The values for the coil bypass factor can be calculated from manufacturer's data by plotting the entering and exiting conditions on a psychrometric chart, and then drawing a line through them to intersect the saturation line. This intersection is the apparatus dew point temperature. Using this point, along with Eq. (IV.11), a series of CBF values can be determined and the rated value and modifier functions can be generated.

In the previous section, it was described how the various supply air and space temperatures are calculated. During this process it was necessary to know the range of dry-bulb temperatures of the supply air that could be made available to the space. This required the estimation of equipment capacity before the entire problem could be solved. To avoid iteration, the previous hour's mixed air wet-bulb temperature is used to estimate the sensible capacity using Eq. (IV.10). Then, the minimum supply air temperature can be calculated as

$$T_{exit} = T_{entering} - \frac{QCS}{1.08 * CFM} \tag{IV.14}$$

where

$T_{entering}$ = the estimated entering dry-bulb air temperature, using an extrapolation of the return air dry-bulb temperature, along with a simulation of outside air controls.

Thus, the capacity limits are known from this estimate. Now, based upon the supply air temperature control method (constant, scheduled, reset, warmest zone, or coldest zone), it is possible to calculate the actual supply air temperature and all the zone (space) temperatures. From the resulting return air and mixed air temperatures, both the coil entering and exiting dry-bulb temperatures are known and the sensible cooling load can be calculated.

It is then possible to use Eq. (IV.11) to calculate T_{surf} and then calculate the saturation humidity ratio at this temperature, W_{surf}.

To solve the moisture problem, a moisture balance is first established for the system (see Fig. IV.8)

$$[CFM * W_r] + [CINF * W_r] = [CFM * W_{exit}] + [CINF * W_0] + \Delta W_r \,, \qquad \text{(IV.15)}$$

where

W_r = humidity ratio of the return air,

W_0 = humidity ratio of the outdoor air,

CINF = outside air infiltration rate,

W_{exit} = humidity ratio of the air leaving the coil, that is, entering the ZONEs, and

ΔW_r = the moisture added within the ZONE by internal sources.

Solving for W_r and letting F = CINF/CFM,

$$W_r = \frac{W_{exit} + (F * W_0) + \Delta W}{1 + F}. \qquad \text{(IV.16)}$$

where ΔW is ΔW_r/CFM.

The mixed (outside and return) air humidity ratio ($W_{entering}$), in terms of the return air and outdoor air humidity ratios (W_r and W_0 respectively), is

$$W_{entering} = [P_0 * W_0] + [(1 - P_0) * W_r], \qquad \text{(IV.17)}$$

where

P_0 = the ratio of outside air flow to total supply air flow.

Combining Eqs. (IV.16) and (IV.17), plus the dry coil assumption that $W_{exit} = W_{entering}$,

$$W_{entering} = W_0 + \left[\frac{1 - P_0}{F + P_0} * \Delta W \right] \qquad (IV.18)$$

or

$$W_r = W_0 + \frac{\Delta W}{F + P_0}.$$

If the coil entering humidity ratio ($W_{entering}$), calculated in Eq. (IV.18), is larger than the coil surface humidity ratio at saturation, the dry coil assumption is incorrect. In this case, Eqs. (IV.12), (IV.16), and (IV.17) are combined to get

$$W_r = \frac{(CBF * P_0 * W_0) + [(1 - CBF) * W_{surf}] + \Delta W + (F * W_0)}{(1 + F - CBF) * (1 - P_0)}. \qquad (IV.19)$$

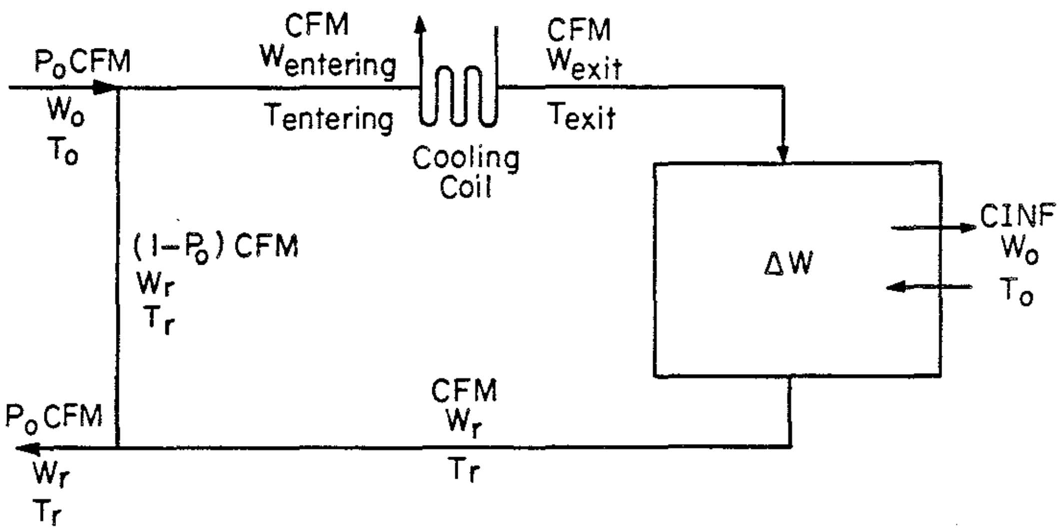

Fig. IV.8. System moisture balance.

It is now possible to reapply Eqs. (IV.12) and (IV.17) to calculate the coil entering and exiting humidity ratios, thus calculating the enthalpy change across the coil.

For direct expansion packaged equipment, the energy input to the compressor-condenser section is calculated next. DOE-2 characterizes devices of this type in terms of energy input ratios; that is, the ratio of energy input to load handled. For electric direct expansion cooling equipment, the electric input ratio (EIR) is used. All the energy input ratios are defined in terms of the equipment capacity

$$EIR_{op} = \frac{Q_{elec}}{QCT_{op}} \tag{IV.20}$$

where

QCT_{op} is the operating capacity or the capacity at the current operating conditions, and

EIR_{op} is the operating electric input ratio.

The EIR_{op} is calculated as a product of the rated EIR and two modifier functions. The first modifier function accounts for off-rated temperatures and the second for part-load operating conditions,

$$EIR_{op} = \text{COOLING-EIR} * \text{COOL-EIR-FT}(T_1,T_2) * \text{COOL-EIR-FPLR(PLRC)} \tag{IV.21}$$

where

T_1,T_2 are as described earlier, and

PLRC is the total cooling part load ratio (cooling load/operating capacity).

Actually, the EIR_{op} is a bit more complex than described above. Generally, there are three ranges of equipment operation. In order of decreasing load, they are (1) a range, just below full load, within which the compressor can unload, (2) a range within which a hot gas bypass is engaged, and (3) a lower range within which the compressor cycles on and off as needed. Only the upper range is meant to be described by the COOL-EIR-FPLR curve.

As can be seen in Fig. IV.9, it is assumed that, within the bypass range, the electric energy input is constant and equal to the value defined by the curve COOL-EIR-FPLR evaluated at PLRC = MIN-UNLOAD-RATIO. It can further be seen that, within the cycling range, the energy input is assumed to follow a linear relationship down through zero from the value within the bypass range.

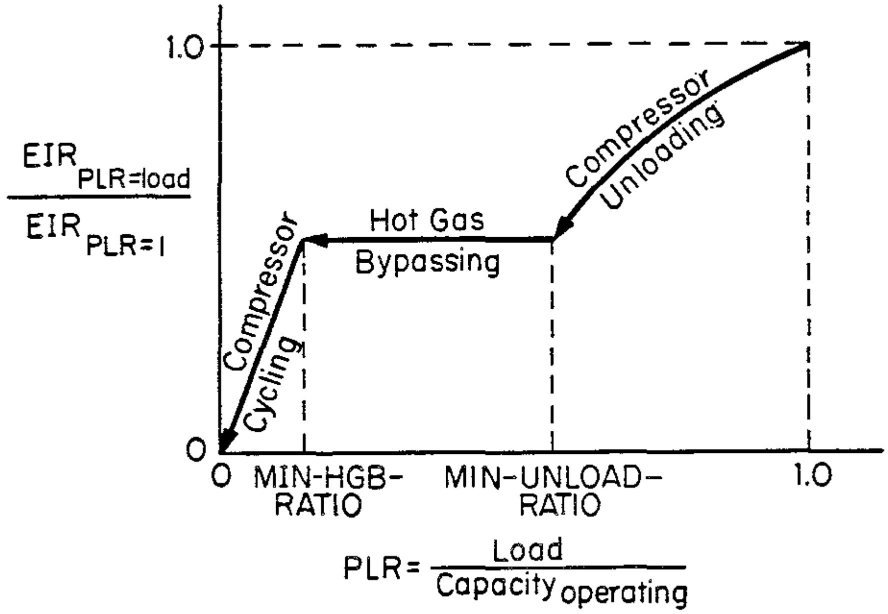

Fig. IV.9. Electric input ratio versus part-load ratio for direct expansion cooling units.

For the simulation of heating equipment, similar concepts are used. The main difference is that, except for heat pumps, the heating capacity is constant and independent of operating conditions. Hot water coil loads are passed directly to the PLANT program. Gas and oil furnaces, electric resistance heaters and heat pumps are simulated in SYSTEMS, passing only the utility load to PLANT.

$$QHT_{op} = \text{HEATING-CAPACITY} * \text{HEAT-CAP-FT}(T_1,T_2) \qquad \text{(IV.22)}$$

where

HEAT-CAP-FT(T_1,T_2) = 1.0, except for heat pumps,

T_1 = the outdoor dry-bulb temperature for air-to-air heat pumps and the water temperature for water-to-air heat pumps, and

T_2 = indoor dry-bulb temperature.

For gas and oil furnaces, the energy input is calculated in terms of the heat input ratio (HIR). The HIR is the ratio of heat input to load handled

$$HIR_{op} = \frac{Q_{fuel}}{QHT_{op}} . \qquad (IV.23)$$

The operating heat input ratio is a product of the full load HIR and a part load modifier

$$HIR_{op} = FURNACE\text{-}HIR * FURNACE\text{-}HIR\text{-}FPLR(PLRH) \qquad (IV.24)$$

where

PLRH is the ratio of furnace load to capacity.

The furnace load during a partial operation hour may be affected by induced infiltration (draft), when the furnace is off. This effect, if present, can be simulated through the use of the keyword FURNACE-OFF-LOSS. This function expresses the induced load as a fraction of unused capacity.

For heat pumps, the electrical energy input is calculated as the product of the operating capacity and electric input ratio

$$Q_{elec} = QHT_{op} * EIR_{op}. \qquad (IV.25)$$

Just as with cooling, the operating EIR is a product of the rated EIR and two modifier functions, one for off-rated temperatures and the other for part load conditions

$$EIR_{op} = HEATING\text{-}EIR * HEAT\text{-}EIR\text{-}FT(T_1,T_2) * HEAT\text{-}EIR\text{-}FPLR(PLRH) \qquad (IV.26)$$

For air-to-air heat pumps, the addition of a defrost system and auxiliary electric resistance heater can also be simulated. Through the use of keywords DEFROST-T and DEFROST-DEGRADE, the user may specify the outdoor dry-bulb temperature below which the defrost system is activated and the amount of defrost time as a function of outdoor conditions. Through the use of keywords ELEC-HEAT-CAP, MAX-ELEC-T, and MIN-HP-T, the user can specify the capacity of the auxiliary heater and the outdoor dry-bulb temperature below which it can operate, as well as the outdoor dry-bulb temperature below which the heat pump can no longer operate.

In addition to the types of heating devices already discussed, the user may augment or replace the default system heating equipment with baseboard heaters. Baseboard output may be controlled either as a function of outdoor dry-bulb temperature (independent of zone temperature) or by the zone thermostat (in response to zone temperature). Thermostatically controlled baseboards are sequenced on first in response to a zone heating load; the primary HVAC system, if present, is activated only after the baseboards are operating at maximum output.

1.4 Interactions of Equipment Control Systems

Although the user selects the generic type of system, with the SYSTEM-TYPE keyword, the details of the hourly simulation and resultant energy calculation can be greatly affected by the choice of keyword values that describe the control options. Some of these effects have already been mentioned for control or part load operation of compressor-condenser units. The space thermostat, cooling coil, mixed air controls, and other control systems can have similar dramatic effects on the energy consumption estimates. In general, there are keywords that allow the user to describe the set points and sequencing of most of the available control systems.

As earlier described, the user-supplied HEAT-TEMP-SCH and COOL-TEMP-SCH together with the THROTTLING-RANGE, define the three action bands of the physical space thermostat. The HEAT-TEMP-SCH defines the midpoint of the heating action range and the COOL-TEMP-SCH defines the midpoint of the cooling action range. If these two values are separated by more than one THROTTLING-RANGE, a dead band has been defined. Within the dead band the equipment action is the same as at the bottom of the cooling action band. If these two values are separated by less than one THROTTLING-RANGE, the program assumes a mistake has been made and then calculates two new thermostatic values, which are centered on the midpoint of the users values, but are separated by one THROTTLING-RANGE.

The actual actions that occur when the zone temperature is within the heating and cooling ranges vary, based on the type of equipment. The cooling range is used to (1) cycle cooling equipment on and off in zonal systems or (2) control the volume and/or temperature in central air-handler systems. If a system has no cooling capability, it is not necessary to specify COOL-TEMP-SCH. Similarly, if a system has no heating capability, it is not necessary to specify HEAT-TEMP-SCH. If multiple types of equipment are present that are controlled in a single temperature control range, they are sequenced in the following manner:

Heating Range (from the top; that is, on a fall in ZONE temperature within the heating action range)

1. Increase the supply air temperature (if SYSTEM-TYPE = DDS, MZS, PMZS, and HVSYS if HEAT-CONTROL = COLDEST)
2. Increase the baseboard output (only if thermostatically controlled from within the zone)
3. Increase the reheat coil output
4. Increase the air volume (only if THERMOSTAT-TYPE = REVERSE-ACTION)

Cooling range (from the bottom; that is, on a rise in ZONE temperature within the cooling action range)

1. Decrease the supply air temperature (if COOL-CONTROL = WARMEST)
2. Increase the supply air volume

Thus, it can be seen that neither a dual duct system nor a reheat system use the COOL-TEMP-SCH unless COOL-CONTROL = WARMEST and/or MIN-CFM-RATIO is less than 1.0. If both these options are selected, the temperature of the supply air will remain at the minimum until all zone temperatures are within the bottom half of the THROTTLING-RANGE. In a similar manner, a variable air volume system has no need for a HEAT-TEMP-SCH unless a reverse action thermostat, a reheat coil, and/or zone-controlled baseboards have been specified. The actions, within these temperature ranges, for the various types of systems can be found in Table IV.1.

The MAX-HUMIDITY and MIN-HUMIDITY keywords place relative humidity control on the return air stream. If the return air relative humidity falls below the specified MIN-HUMIDITY, steam or hot-water is injected into the supply air. The resultant load is always passed on to the PLANT program as a steam or hot-water load. If the return air humidity goes above the specified MAX-HUMIDITY, the cold supply air temperature is reset downward toward the minimum until the specified MAX-HUMIDITY level is maintained or the cooling coil capacity (or MIN-SUPPLY-T) is reached. The downward reset of the supply air temperature, to reduce the relative humidity, can often defeat the action of a zone-controlled cooling coil (PSZ, SZRH, or systems with COOL-CONTROL = WARMEST). Also, the simulation of this control scheme becomes inaccurate for large values of temperature reset action. This inaccuracy is caused by the non-iterative nature of the simulation. The reset of the supply air temperature can cause a very different space thermostat and terminal unit performance from the initial calculation. Because the detailed zone calculation is not redone, errors may result.

Although no keyword is available to the user to specify an economizer controller set point, the program simulates this equipment. The controller that mixes outside and return air is simulated as having the same set point as the cold deck controller. The controller compensates for heat gain caused by a blow-through fan arrangement, if present. This controller opens (modulates) the moveable outside air damper (if available) in response to a rising mixed air temperature. Thus, if the outdoor dry-bulb temperature is above the cooling coil set point, it may not be possible to obtain the desired cooling. In fact, the system may be inducing an extra cooling load if the return air temperature is less than the outdoor air dry-bulb temperature. For this reason, there is an upper limit override on the economizer that specifies the outdoor dry-bulb temperature at which the outdoor air damper is forced back to its minimum position. This limit is specified by the ECONO-LIMIT-T keyword. Additionally, there may be an enthalpy-controlled economizer that resets the damper to its minimum position if the outdoor air enthalpy is greater than the return air enthalpy (otherwise, action is similar to that already described). This additional limitation is obtained by specifying the keyword OA-CONTROL = ENTHALPY, instead of the default value of TEMP.

A variable volume supply and/or return air fan is simulated assuming the existence of a pressure control system. It is further assumed that this results in a constant pressure differential across the outside air damper. The minimum outside air fraction is, therefore, only relative to design flow rate (not the current operating supply air flow rate). As the supply air flow rate drops, the constant pressure differential across the outside air damper insures a constant volume of outside air, thus resulting in an increasingly larger outside air fraction, relative to the supply air flow rate.

TABLE IV.1

ACTIONS SIMULATED BY SPECIFYING
COOL-TEMP-SCH AND HEAT-TEMP-SCH FOR EACH SYSTEM-TYPE

	Heating (on a fall in ZONE temperature)		Cooling (on a rise in ZONE temperature)	
SYSTEM-TYPE	Action Simulated by HEAT-TEMP-SCH	Additional Required Keyword(s) and Value(s)	Action Simulated by COOL-TEMP-SCH	Additional Required Keyword(s) and Value(s)
MZS,DDS,PMZS	Increase heating air temperature Increase baseboard output Mix hot and cold air Increase supply air volume	HEAT-CONTROL = COLDEST BASEBOARD-CTRL = THERMOSTATIC - MIN-CFM-RATIO < 1 and THERMOSTAT-TYPE = REVERSE-ACTION	Reduce cooling air temperature Increase supply air volume	COOL-CONTROL = WARMEST MIN-CFM-RATIO < 1
VAVS,PVAVS CBVAV,RHFS	Increase baseboards output Increase reheat coil output Increase supply air volume	BASEBOARD-CTRL = THERMOSTATIC REHEAT-DELTA-T ≠ 0 MIN-CFM-RATIO < 1 and THERMOSTAT-TYPE = REVERSE-ACTION	Reduce supply air temperature Increase supply air volume (not on RHFS)	COOL-CONTROL = WARMEST MIN-CFM-RATIO < 1
SZRH, PSZ	Increase reheat (subzone only) Increase supply air temperature	- -	Reduce supply air temperature	-
TPFC,FPFC,HP, RESYS,PTAC	Increase zone heating coil output	-	Increase zone cooling coil output	-
UHT,UVT	Close OA damper (UVT only) Increase heating coil output	- -	Open OA damper (UVT only)	-
FPH	Increase heat addition	-	Unused	-
HVSYS	Increase supply air temperature Increase baseboards output Increase reheat coil output	HEAT-CONTROL = COLDEST BASEBOARD-CTRL = THERMOSTATIC REHEAT-DELTA-T ≠ 0	Unused	-

TABLE IV.1 Continued

	Heating (on a fall in ZONE temperature)		Cooling (on a rise in ZONE temperature)	
SYSTEM-TYPE	Action Simulated by HEAT-TEMP-SCH	Additional Required Keyword(s) and Value(s)	Action Simulated by COOL-TEMP-SCH	Additional Required Keyword(s) and Value(s)
TPIU,FPIU	Increase zone heating coil output	-	Reduce cooling air temperature	COOL-CONTROL = WARMEST
			Increase zone cooling coil output	-
SZCI	Increase baseboard output	BASEBOARD-CTRL = THERMOSTATIC	Reduce cooling air temperature	COOL-CONTROL = WARMEST
	Increase reheat coil output	REHEAT-DELTA-T $\neq$ 0	Increase supply air volume	-
SUM	Increase heat addition	-	Increase heat extraction	-

1.5 Design Calculations

As described in previous sections, many equipment design parameters must be known by the program before the hourly simulation can proceed. Most of these parameters may be specified by the user, through the keyword values of a thermal ZONE or HVAC SYSTEM. To make the program easier to use, especially in the early stages of analysis, a set of procedures has been developed to calculate most design parameters if the user has not provided complete information. Before the simulation can start, all air flow rates, equipment capacities, and off-rated performance modifier functions must be known. The default off-rated performance modifier functions (curves) are retrieved from a library. These default curves were calculated once, and stored in the library, for what was considered typical equipment for each type of system. If, upon examination, the user finds these curves to be undesirable, they may be replaced with better data by using the CURVE-FIT instruction (see BDL, Chap. II).

Air flow rates and coil capacities, however, cannot be precalculated. These values usually depend entirely upon heating and cooling requirements. Again, the user may specify the values of all air flow rates and coil capacities, by using the keywords provided for this purpose. If any flow rate or capacity is left unspecified, the program calculates it by using whatever information has been supplied by the user, plus some values calculated within the SYSTEMS or LOADS programs.

Basically, the following relationship must hold true:

$$Q = 1.08 * CFM * \Delta T \qquad \text{(IV.27)}$$

where

Q is the sensible cooling (or heating) load,
CFM is the supply air flow rate, and
ΔT is the temperature difference.

Usually, the ΔT is known from user-specified values. Keyword values for DESIGN-HEAT-T and DESIGN-COOL-T are required for all conditioned zones. These values, together with MAX-SUPPLY-T and MIN-SUPPLY-T (or REHEAT-DELTA-T for reheat coil systems), define the zone temperature and supply air temperature values for ΔT. If the user has specified the CFM, the Q can be directly calculated. Similarly, if the user has supplied Q, the CFM can be calculated. If neither CMF or Q has been supplied, the Q value is taken as the peak load calculated in the LOADS program (found in LS-B) and CFM is then calculated in the SYSTEMS program. If both the CFM and the Q values have been specified, they take precedence over ΔT.

Once Eq. (IV.27) has been applied for each zone, taking into account exhaust air, it is then possible to calculate the return air and mixed air temperatures for both the heating and cooling modes. Then, the sensible coil capacities for the central air-handler can be calculated. The latent cooling load is calculated as discussed in a previous section. Once the coil and fan capacities have been calculated for the peak cooling and heating conditions, it is possible to calculate the rated capacities. Rated capacity conditions, within the program, are according to the standards established by the Air-Conditioning and Refrigeration Institute. These conditions are: 80°F indoor entering dry-bulb temperature, 67°F indoor entering wet-bulb temperature, and 95°F outdoor dry-bulb temperature for cooling devices; 70°F indoor entering dry-bulb temperature and 47°F outdoor dry-bulb temperature for heat pumps in the heating mode. Report SV-A always contains the rated capacities.

For systems with variable air flow rate capabilities, the CFM and capacity calculations can be a bit more complex. In the zone-by-zone application of Eq. (IV.27), usually the cooling load, not the heating load, will determine the value of CFM. If a MIN-CFM-RATIO has not been specified, it will be calculated from either the heating or ventilation requirements. Additionally, the fan in the central air handler will be sized based upon the building coincident peak load (found in Report LS-C), instead of the sum of the zone design air flow rates, if the keyword SIZING-OPTION = COINCIDENT (default for VAVS, PVAVS). This can lead to problems if a night setback or setup is used, because the morning load may be too large for the available air flow rate.

2. DESIGN CALCULATIONS (Subroutine DESIGN)

Overview

The design subroutine (DESIGN) ensures that all the various quantities needed for the system simulation are given values. These values are either

(1) specified by the user,
(2) defaults built into the program, or
(3) calculated for peak cooling and heating conditions that were determined in the LOADS program.

This subroutine also ensures consistency among the multiple values of related data. The hourly simulation requires:

(1) a value for the air flow rate (for air systems) for each conditioned zone,
(2) a heating and cooling capacity for each system, unit, or coil,
(3) the electrical consumption of fans and direct expansion condenser-compressor arrangements,
(4) minimum and maximum air flow rates for variable-air volume flow equipment,
(5) outside ventilation air flow rates, and
(6) other controller set point or operational information.

Because the built-in calculations of this subroutine may not always do things as the user wishes, it is sometimes necessary for critical keywords to be specified in such a manner that will result in the desired sizing.

The design calculations are performed for each SYSTEM specified in a PLANT-ASSIGNMENT instruction and for each ZONE in one of these SYSTEMs. The results of the calculations can be found in the SYSTEMS verification report, SV-A.

Calculation Outline

A. Correct the zone peak heating and cooling loads if the user has specified SIZING-OPTION = ADJUST-LOADS in the ZONE instruction.

For each SYSTEM that has a PLANT-ASSIGNMENT instruction:

B. Calculate the supply air and return air fan heat gain and energy consumption at the design air flow rate.

C. Calculate for each ZONE attached to this SYSTEM

1. the outside ventilation air flow rate,
2. the total zone supply air flow rate,
3. the heating capacity for zone coil systems (zonal systems),
4. the cooling capacity for zone coil systems (zonal systems),
5. the minimum supply air flow rate for non-zonal systems (central systems), and
6. the sum of the various quantities needed for the central air handler calculation, if present.

D. Calculate the supply air flow rate for the coincident-sized supply fan.

E. Adjust each program-calculated zone supply air flow rate, heating rate, and cooling rate for a user-specified central air handler fan size.

F. Calculate the capacity of the central air handler heating coil.

G. Calculate the capacity of the central air handler cooling coil.

Calculation Algorithms

A. Correct the zone peak heating and cooling loads if the user has specified SIZING-OPTION = ADJUST-LOADS in the ZONE instruction.

Adjust the peak heating and cooling loads for each zone, to account for any difference between the design temperatures that were specified in the SYSTEMS program and the reference-calculation temperature that was specified in the LOADS program.

The calculation in the LOADS program of the zone heating and cooling loads was performed at a constant zone TEMPERATURE that was specified, for that zone by the user. The design calculations performed by the SYSTEMS program will use the peak heating and cooling loads to size the equipment, assuming no sizing is specified by the user. Because the zone DESIGN-HEAT-T and DESIGN-COOL-T, specified in the SYSTEMS input, may be different from the LOADS program TEMPERATURE, it is desirable to adjust the LOADS program peaks to account for this difference. This adjustment of peak loads used for sizing is especially important under the following conditions:

a. When a zone has an INTERIOR-WALL that is shared with another zone and the load across the INTERIOR-WALL is a significant contributor to the peak load in the zone, and/or

b. when the LOADS calculation TEMPERATURE is significantly different from the DESIGN-HEAT-T or DESIGN-COOL-T and this difference can have a significant effect on the peak load used for equipment sizing.

The former condition usually occurs when the zone on the other side of the INTERIOR-WALL is an UNCONDITIONED or PLENUM-type zone. Thus, that zone will have a temperature, at the time of the peaks, that is significantly different from its LOADS TEMPERATURE.

If the SIZING-OPTION (in the ZONE instruction) has been set equal to ADJUST-LOADS, the LOADS program peak values for this zone will be modified to account for these differences.

1. For infiltration and external wall thermal conductance, the steady state heat transfer correction caused by the temperature differentials for both heating and cooling are calculated.

$$\text{QHEXT} = [\text{<CONDUCE>} + \text{CONS(1)} * \text{<CFMIPEAKH>}] * (\text{TEMPERATURE} - \text{DESIGN-HEAT-T}) \text{ and} \tag{IV.28}$$

$$\text{QCEXT} = [\text{<CONDUCE>} + \text{CONS(1)} * \text{<CFMIPEAKC>} * (\text{TEMPERATURE} - \text{DESIGN-COOL-T}), \tag{IV.29}$$

where

<CONDUCE> = the total thermal conductance of all exterior surfaces for this zone,

<CFMIPEAKH> = the infiltration air flow rate at peak heating,

<CFMIPEAKC> = the infiltration air flow rate at peak cooling,

TEMPERATURE = the LOADS program reference temperature,

CONS(1) = 1.08 Btu-min/hr-ft^3-°F. CONS(1) is discussed in greater detail in the next subsection.

2. For heat transfer across interior walls, a correction is made for that heat transfer that was not accounted for by LOADS (caused by the different reference temperatures).

$$\text{QHINT} = [(\text{DESIGN-HEAT-T}_j - \text{DESIGN-HEAT-T}) - (\text{TEMPERATURE}_j - \text{TEMPERATURE})] * \text{CONDUC and} \tag{IV.30}$$

$$\text{QCINT} = [(\text{DESIGN-COOL-T}_j - \text{DESIGN-COOL-T}) - (\text{TEMPERATURE}_j - \text{TEMPERATURE})] * \text{CONDUC}, \tag{IV.31}$$

where

j subscript = the <u>jth</u> attached space and

CONDUC = the total thermal conductance ($\Sigma \mu A$) of interior walls that are connecting the two spaces.

Now, the peak steady state values calculated by the LOADS program are modified.

$$\text{<QMAX>} = QC_L + \text{QCINT} + \text{QCEXT and} \tag{IV.32}$$

$$\text{<QMIN>} = QH_L + \text{QHINT} + \text{QHEXT} \tag{IV.33}$$

where

QC_L is the peak cooling load from LOADS and
QH_L is the peak heating load from LOADS.

For each SYSTEM specified in each PLANT-ASSIGNMENT instruction, perform the necessary design calculations.

B. Calculate the supply air and return air fan heat gain and energy consumption at the design air flow rate.

There are two ways to specify both the fan energy consumption and the air stream temperature rise at design conditions. Either (1) air pressures and fan efficiencies are specified, allowing the program to assume that all fan energy consumption causes an air stream temperature rise, or (2) the electrical power consumed per CFM of air flow and the air stream temperature rise are explicitly specified. If the user has input SUPPLY-EFF and SUPPLY-STATIC, such that the variable

$$\text{DTS} = \frac{\text{SUPPLY-STATIC}}{\text{SUPPLY-EFF}}$$

is not zero, the air stream temperature rise and the fan electrical energy consumption, at the design air flow rate, are calculated as

$$\text{SUPPLY-DELTA-T} = \text{DTS} * \text{CONS}(3), \text{ and} \tag{IV.34}$$

$$\text{SUPPLY-KW} = \frac{\text{SUPPLY-CFM} * \text{DTS}}{8520.0}, \tag{IV.35}$$

where 8520 converts (standard cfm x inches of water)/efficiency to kilowatts, that is,

$$\frac{\text{ft}}{12\ \text{in}} \times \frac{62.27\ \text{lb}}{\text{ft}^3} \times \frac{\text{Btu}}{778\ \text{ft-lb}} \times \frac{\text{kW}}{3413\ \text{Btu/hr}} \times \frac{60\ \text{min}}{\text{hr}} =$$

$$.000117\ \frac{\text{min-kW}}{\text{ft}^3\text{-in}} \text{ or } 8520\ \frac{\text{ft}^3\text{-in}}{\text{min-kW}}$$

and CONS(3) = 0.363 at standard conditions.

The value of CONS(3) is actually adjusted on an hourly basis, along with the other such constants, for calculating the specific heat of air [CONS(1)] and the heat of vaporization [CONS(2)].

$$\text{CONS}(1) = \frac{(0.24 + .44 * \text{HUMRAT}) * 60.0 * \text{PATM}}{0.754 * (\text{T} + 459.7) * (1.0 + 1.605 * \text{HUMRAT})} \tag{IV.36}$$

where

0.24 = the specific heat of air (Btu/lb-°F)
0.44 = the specific heat of water vapor (Btu/lb-°F)
HUMRAT = the outdoor humidity ratio (lbs H_2O/lb dry air),
60 = the time conversion factor (min/hr)
PATM = the atmospheric pressure (inch of Hg),
1.605 = the ratio of the molecular weight of dry air (28.9645) to the molecular weight of water vapor (18.01534),
.754 = the factor for converting air and water partial pressures into inches of mercury (ft^2-in/lb-°R); that is,

$$\frac{1545.32 \dfrac{\text{lb force}}{\text{ft}^2}\,\text{ft}^3}{(\text{lb mole})\ (\text{deg R})} \Bigg/ 28.9645\ (\text{moles}) = 53.352\ \frac{(\text{ft lb force})}{(\text{lb mass})\ (\text{deg R})}$$

and

$$53.352\ \frac{(\text{ft lb force})}{(\text{lb mass})\ (\text{deg R})} \Bigg/ 70.7262\ \frac{\text{lb force}}{\text{ft}^2\text{-inch Hg}}$$

or

$$.754\ \text{ft}^2\text{-in/lb-°R, or } 1.326\ \frac{\text{lb-°R}}{\text{ft}^2\text{-in}},$$

T = the dry-bulb temperature, usually the mixed (return and outside ventilation) air temperature (°F), and

459.7 = the factor to convert T to absolute temperature.

$$\text{CONS(1)} = \frac{\text{specific heat of dry air + specific heat of water vapor}}{\text{specific volume of dry air}}.$$

CONS(1) = 1.08 for sensible heating and cooling design calculations (at standard conditions) (Btu-min/hr-ft^3-°F).

$$\text{CONS(2)} = \frac{1061.0 * 60.0 * \text{PATM}}{0.754 * (\text{T} + 459.7) * (1.0 + 1.605 * \text{HUMRAT})} \qquad \text{(IV.37)}$$

where

1061 = the enthalpy of saturated water vapor at 0°F (Btu/lb) and all the other variables and constants are as previously defined.

CONS(2) = 4790.0 for latent heating and cooling design calculations (at standard conditions) (Btu-min/hr-ft^3), and

$$\text{CONS}(3) = \frac{.3996}{\text{CONS}(1)} \tag{IV.38}$$

where

CONS(3) converts inches of water to °F, that is,

$$Q = \frac{Hp}{\varepsilon} = 1.08 \times \text{cfm} \times \Delta T, \text{ (Hp is horse power and } \varepsilon \text{ is efficiency), or}$$

$$\Delta T = \frac{Hp}{1.08 \times \text{cfm} \times \Delta T}$$

$$1 \text{ Hp} = \frac{\dfrac{62.27\text{lb}}{\text{ft}^3} \times \dfrac{60 \text{ min}}{\text{hr}}}{\dfrac{12 \text{ in}}{\text{ft}} \times \dfrac{778 \text{ ft-lb}}{\text{Btu}} \times \dfrac{2544 \text{ Btu}}{\text{hr-Hp}}} = .000157 \frac{\text{min-Hp}}{\text{ft}^3\text{-in}}$$

$$\Delta T = \frac{.000157 \dfrac{\text{min-Hp}}{\text{ft}^3\text{-in}} \times 2544 \dfrac{\text{Btu}}{\text{hr-Hp}}}{1.08 \dfrac{\text{Btu/min}}{\text{hr-ft}^3\text{-°F}} \times \dfrac{\text{ft}^3}{\text{min}} \times \varepsilon} .$$

The numerator divided by the first term in the denominator [1.08 = CONS(1)] is defined as CONS(3),

$$\text{CON}(3) = \frac{.3996}{\text{CONS}(1)} \text{ °F/in.}$$

CONS(3) = 0.363 for design calculation (at standard conditions) (°F/in).

Because these functions [CONS(1), CONS(2), and CONS(3)] are only slightly dependent upon the humidity ratio, the outdoor value of humidity ratio (HUMRAT) is used instead of the mixed air value of humidity ratio. The mixed air temperature is used as the point for evaluating these functions because it approximates, or equals, the central cooling and heating coil entering conditions. Thus, all air densities are calculated based upon conditions entering the coils.

Equations (IV.34) and (IV.35) assume that all electrical input is added to the air stream as fan heat gain. Additionally, it is assumed that this heat gain takes place entirely at the fan itself. In reality, some heat gain is realized at the fan, some is realized as coil and ductwork resistance, and the rest is realized as the air enters the conditioned space. If the user has specified that the MOTOR-PLACEMENT is OUTSIDE-AIRFLOW, only the mechanical fan energy is added to the air stream as heat gain. Thus, DTS is calculated as

$$\text{DTS} = \frac{\text{SUPPLY-STATIC}}{\text{SUPPLY-MECH-EFF}} . \tag{IV.39}$$

If SUPPLY-MECH-EFF has not been specified by the user, it will default to either SUPPLY-EFF/.9 or 1.0, whichever is smaller.

Similarly, for return air fans

$$\text{DTR} = \frac{\text{RETURN-STATIC}}{\text{RETURN-EFF}} , \tag{IV.40}$$

$$\text{RETURN-DELTA-T} = \text{DTR} * \text{CONS}(3), \text{ and} \tag{IV.41}$$

$$\text{RETURN-KW} = \frac{\text{RETURN-CFM} * \text{DTR}}{8520.0}, \tag{IV.42}$$

where 8520 converts (standard cfm x inches of water)/efficiency to kilowatts.

If the values for DTS or DTR are equal to zero, the values of SUPPLY-KW, SUPPLY-DELTA-T, RETURN-KW, and RETURN-DELTA-T are either as specified by the user or are as defaulted.

C. Calculate for each ZONE attached to this SYSTEM (depending upon the SYSTEM-TYPE):

<u>Step 1. the outside ventilation air flow rate</u>

First, calculate the minimum ventilation requirement (<VENTMIN>). There are, at the zone level, three keyword options through which the user may specify this value.

$$\langle\text{VENTMIN}\rangle = \text{OUTSIDE-AIR-CFM, if it is specified.} \tag{IV.43}$$

Otherwise,

<VENTMIN> = the larger of (OA-CHANGE * <VOLUME>/60.0)

and

(OA-CFM/PER * <PEOPLE>),

rounded up to the nearest 10 CFM.

After the value of <VENTMIN> has been determined, it is tested to ensure that it is larger than the EXHAUST-CFM. <VENTMIN> is then adjusted for the altitude by multiplying by BPMULT, the building atmospheric pressure multiplier.

$$\text{BPMULT} = \frac{29.91}{\text{BLDGP}}, \text{ rounded up to the nearest 1 per cent} \qquad \text{(IV.44)}$$

where $\text{BLDGP} = 29.92 * e^{-0.0000368 * \text{ALTITUDE}}$.

If the value of <VENTMIN> is still zero, it is calculated as the MIN-OUTSIDE-AIR times the specified, or calculated, ASSIGNED-CFM (as described later).

The total outside air flow rate for the system (OUTA) is also calculated

$$\text{OUTA} = \sum_{nz=1}^{nzones} \text{<VENTMIN>}_{nz} * \text{MULTIPLIER}_{nz}. \qquad \text{(IV.45)}$$

<u>Step 2. the total zone supply air flow rate</u>

The zone design air flow rate (<CFMAX>) can also be calculated, or specified, in a variety of ways.

<CFMAX> = ASSIGNED-CFM, if it has been specified. (IV.46)

Otherwise,

$$\text{<CFMAX>} = \text{the larger of } \frac{\text{AIR-CHANGES/HR * <VOLUME>}}{60.0}$$

and (CFM/SQFT * <AREA>).

If no value has been specified for ASSIGNED-CFM, AIR-CHANGES/HR, or CFM/SQFT,

$$\text{<CFMAX>} = \text{the larger of } \frac{\text{MAX-COOL-RATE}}{\text{CONS(1)} * (\text{DESIGN-COOL-T} - \text{MIN-SUPPLY-T})}$$

$$\text{and } \frac{\text{MAX-HEAT-RATE}}{\text{CONS(1)} * (\text{DESIGN-HEAT-T} - \text{MAX-SUPPLY-T})} \; .$$

However,

$$\text{<CFMAX>} = \frac{\text{<VENTMIN>}}{(1.0 + \text{INDUCTION-RATIO})} \; ,$$

if this calculated value is larger than any of the previously calculated, or specified, values for <CFMAX>.

The algorithms assume that all air flow rates have been specified by the user as standard (sea level) values. The value of <CFMAX> for each zone is adjusted for altitude by multiplying by BPMULT. If the ASSIGNED-CFM was not specified, the value of <CFMAX> is rounded up to the nearest 10 CFM before being adjusted for the altitude. Then, <CFMAX> is multiplied by the SIZING-RATIO.

In the previous expressions, MAX-COOL-RATE and MAX-HEAT-RATE are the peak loads calculated in the LOADS program for each zone, unless the user specifies these values. These values are also used as the design maximum heat addition rate (<ERMIND>) and the design maximum heat extraction rate (<ERMAXD>). By definition in the program, the equipment effect on the zone is always called "heat extraction" (cooling is positive extraction and heating is negative extraction).

$$\text{<ERMIND>} = \text{MAX-HEAT-RATE}, \tag{IV.47}$$

as specified by the user, or from LOADS. If, however, <CFMAX> was specified through any keywords, then

$$\text{<ERMIND>} = \text{<CFMAX>} * \text{CONS(1)} * (\text{DESIGN-HEAT-T} - \text{MAX-SUPPLY-T}).$$

Note that this value does not include the heating energy for baseboard heaters (see BASEBOARD-RATING) or variable air volume systems (see Step 5).

$$<ERMAXD> = MAX\text{-}COOL\text{-}RATE, \tag{IV.48}$$

as specified by the user, or from LOADS. If, however, <CFMAX> was specified through any keywords, then

$$<ERMAXD> = <CFMAX> * CONS(1) * (DESIGN\text{-}COOL\text{-}T - MIN\text{-}SUPPLY\text{-}T).$$

From the description above, it can be seen that the basic relationship

$$Q = 1.08 * CFM * \Delta T \tag{IV.49}$$

is used to either check consistency of the input data or to calculate other required data. Because the Δt is always known (DESIGN-HEAT-T, DESIGN-COOL-T, MIN-SUPPLY-T, and MAX-SUPPLY-T are required in most systems), given a value for Q, the CFM can be calculated. Conversely, given a CFM, the Q can be calculated. If both are specified, CFM takes precedence and the value of Q is made to agree with the CFM.

Step 3. the heating capacity for zone coil systems (zonal systems)

For systems with heating coils located in the zone, it is necessary first to determine if the coil capacity has been specified by the user or if the coil capacity can be calculated by the program. For systems with reheat coils, the capacity is set by the value specified by the user for REHEAT-DELTA-T. For fan coils, unit heaters, unit ventilators, water-to-air heat pumps, and induction units, the coil heating capacity is calculated to meet the space design conditions (assuming the heating capacity has not been specified). If the heating capacity has been specified by the user, the design heating rate (<ERMIND>) can be recalculated to match this specification.

For zone coils, not in reheat or induction systems, the heating coil capacity is calculated from an expression similar to Eq. (IV.49), adjusted for off-rated (operating) conditions

$$HEATING\text{-}CAPACITY = \frac{CONS(1) * <CFMAX> * \Delta T}{QHM1}, \tag{IV.50}$$

where CONS(1) and <CFMAX> are as described earlier. QHM1 is an off-rated temperature correction factor. Its value is determined as follows:

$$QHM1 = 1.0, \text{ if } SYSTEM\text{-}TYPE = UHT \text{ or } UVT,$$

but if HEAT-SOURCE = HEAT-PUMP,

$$QHM1 = CVAL(HEAT\text{-}CAP\text{-}FT, DBT, TMZ).$$

Here, HEAT-CAP-FT is a heating capacity performance function that is either specified by the user (see the SYSTEM-EQUIPMENT subcommand and the CURVE-FIT instruction) or is defaulted by the user to the program's internal performance function by the same name (HEAT-CAP-FT). DBT is the larger of DBTMIN (that is, the outdoor dry-bulb temperature at the time of the building peak heating load, from LOADS) and MIN-HP-T (the outdoor dry-bulb temperature below which the heat pump turns off). TMZ is the mixed (outside ventilation and return) air temperature.

If SYSTEM-TYPE = HP,

$$QHM1 = CVAL(HEAT\text{-}CAP\text{-}FT, TMZ, MIN\text{-}FLUID\text{-}T).$$

Here, HEAT-CAP-FT and TMZ are as just defined and MIN-FLUID-T is the minimum allowable temperature (entering the heat pump) for the circulating fluid.

The ΔT in Eq. (IV.50) is the mixed air temperature (TMZ) minus the supply heating air temperature (THZ). To calculate the mixed air temperature, it is required first to know the ratio (PO) of outside ventilation air (<VENTMIN>) to the total supply air (<CFMAX>)

$$PO = \frac{<VENTMIN>}{<CFMAX>}. \qquad (IV.51)$$

Then,

$$TMZ = (PO * DBTMIN) + [(1.0 - PO) * TRZ] + SUPPLY\text{-}DELTA\text{-}T, \qquad (IV.52)$$

where SUPPLY-DELTA-T is the temperature rise in the air stream across the supply air fan. The return air temperature (TRZ) and the temperature of the air leaving the heating coil (THZ) are calculated as,

$$TRZ = DESIGN\text{-}HEAT\text{-}T + \frac{<QPPEAKH>}{CONS(1) * <CFMAX>}, \text{ and} \qquad (IV.53)$$

$$THZ = MAX\text{-}SUPPLY\text{-}T,$$

where DESIGN-HEAT-T is the desired space temperature for design and <QPPEAKH> is the heat from lights into the plenum at the time of the space peak heating load. If the user has specified a zonal type system (UHT, UVT, TPFC, FPFC, TPIU, FPIU, HP, or PTAC), plenums are not allowed; therefore, this load (<QPPEAKH>) is added to the space.

If the HEATING-CAPACITY has been specified by the user, the program recalculates the design heating rate (<ERMIND>), by using either

$$THZ = TMZ - \frac{\text{HEATING-CAPACITY}}{\text{CONS}(1) * \text{<CFMAX>}}, \tag{IV.54}$$

or

$$THZ = \text{MAX-SUPPLY-T, whichever is smaller, and}$$

$$\text{<ERMIND>} = \text{CONS}(1) * \text{<CFMAX>} * (\text{DESIGN-HEAT-T} - THZ). \tag{IV.55}$$

For induction systems, the heating coil capacity needs to take into consideration the supply air flow rate and temperature from the central air handler.

$$Q_{total} = Q_{air\ handler} + Q_{zone}, \text{ and} \tag{IV.56}$$

$$Q_{zone} = \text{HEATING-CAPACITY}_{zone} = \text{CONS}(1) * \text{<CFMAX>} * (TS - THZ), \tag{IV.57}$$

where

$$TS = \frac{TH + (\text{INDUCTION-RATIO} * \text{DESIGN-HEAT-T})}{1.0 + \text{INDUCTION-RATIO}},$$

$$TH = \text{HEAT-SET-T, if HEAT-SET-T is specified, otherwise,}$$

$$TH = \text{MIN-SUPPLY-T, and}$$

$$THZ = \text{DESIGN-HEAT-T} - \frac{\text{<ERMIND>} - \text{BASEBOARD-RATING}}{\text{CONS}(1) * \text{<CFMAX>}}.$$

If the user has specified the HEATING-CAPACITY at the zone level, only the design heat addition rate needs to be recalculated

$$\langle \text{ERMIND} \rangle = \text{MAX-HEAT-RATE} + (\text{HEATING-CAPACITY} - Q_{zone}), \qquad \text{(IV.58)}$$

where Q_{zone} is calculated from Eq. (IV.57).

Step 4. the cooling capacity for zone coil systems (zonal systems)

For fan coils, packaged terminal air conditioners, water-to-air heat pumps, induction systems, and other zonal cooling systems, it is necessary to determine the size of the zone cooling unit. In the case of cooling, the sensible and latent components of the load must be calculated

$$Q_{total} = Q_{sensible} + Q_{latent}. \qquad \text{(IV.59)}$$

The sensible part of the zone cooling load can be calculated in a manner similar to the heating calculation. The ability to adjust for off-rated conditions, however, requires solving the moisture problem first, so that the entering wet-bulb temperature can be calculated

$$Q_{sensible} = \frac{\text{COOL-SH-CAP} - \text{QCM3}}{\text{QCM2}}$$

$$Q_{sensible} = \text{CONS}(1) * \langle \text{CFMAX} \rangle * (\text{TMZ} - \text{TCZ}), \qquad \text{(IV.60)}$$

where

QCM2 = CVAL(COOL-SH-FT,EWB,EDB) [COOL-SH-FT is a correction function to the sensible cooling capacity (COOL-SH-CAP) to adjust for off-rated entering wet-bulb and entering dry-bulb temperatures],

EWB = coil entering wet-bulb temperature,

EDB = MAX-FLUID-T for SYSTEM-TYPE = HP, or the larger of DBTMAX and COOL-FT-MIN for SYSTEM-TYPE = PTAC (DBTMAX is the outdoor dry-bulb temperature at the time of the building peak cooling load and COOL-FT-MIN is the minimum dry-bulb temperature for adjusting COOL-SH-FT),

TMZ = (PO * DBTMAX) + [(1.0 - PO) * TRZ] + SUPPLY-DELTA-T [PO is the ratio of outside ventilation air (<VENTMIN>) to the total supply air (<CFMAX>)],

$$TRZ = \text{DESIGN-COOL-T} + \frac{<\text{OPPEAKC}>}{[\text{CONS}(1) * <\text{CFMAX}>]}, \text{ with}$$

<QPPEAKC> = heat from lights into the plenum, from LOADS, at zone peak cooling load,

TCZ = MIN-SUPPLY-T, and

QCM3 = CONS(1) * <CFMAX> * (1.0 - COIL-BF) * (TMZ - 80.0) for SYSTEM-TYPE = HP and PTAC (the off-design space dry-bulb temperature adjustment) or 0.0 for other SYSTEM-TYPEs.

It can be seen that to calculate QCM2 for Eq. (IV.60) requires knowing the entering wet-bulb temperature. Thus, a moisture balance on the zone and unit must be solved. Start by equating the moisture gains and losses

$$(<\text{CFMAX}> * WR) + (<\text{CFMIPEAKC}> * WR) = (<\text{CFMAX}> * WC) + (<\text{CFMIPEAKC}> * WMAX) + \Delta W, \tag{IV.61}$$

where

WR = the space humidity ratio, which is also the return air humidity ratio,

<CFMIPEAKC> = the infiltration CFM, from LOADS, at the time of the cooling peak load,

WC = the cooling coil exit humidity ratio,

WMAX = the outdoor humidity ratio, from LOADS, at the time of the building cooling peak load, and

ΔW = <QLPEAKC>/CONS(2) = the latent heat gain in the space, with

<QLPEAKC> = the space latent heat gain, from LOADS, at the cooling peak load.

If

$$F = \frac{<\text{CFMIPEAKC}>}{<\text{CFMAX}>} \text{ and } DW = \frac{\Delta W}{<\text{CFMAX}>},$$

solving for WR,

$$WR = \frac{WC + DW + (F * WMAX)}{1.0 + F}. \qquad (IV.62)$$

The mixed air humidity ratio (WM) is calculated from the mixing of outside ventilation air and room return air

$$WM = (PO * WMAX) + [(1.0 - PO) * WR]. \qquad (IV.63)$$

By combining Eqs. (IV.62) and (IV.63), solving for WM, and assuming a dry coil (WM = WC),

$$WM = WMAX + \left\{\left(\frac{1.0 - PO}{F + PO}\right) * DW\right\} . \qquad (IV.64)$$

If the amount of outside ventilation air plus infiltration air is zero, a rare condition, the right-hand side of this expression is replaced with (WMAX + DW). Now it is necessary to estimate the coil dew point temperature to check the dry surface condition assumption. To do this, it is necessary to estimate the coil bypass factor and then apply the bypass relationship. The bypass factor is estimated to be close to design conditions. Applying the bypass relationship, the program calculates the cooling coil surface temperature (TSURF) and the saturation humidity ratio (WSURF) at TSURF

$$TSURF = \frac{TCZ - (CBF * TMZ)}{1.0 - CBF} , \qquad (IV.65)$$

where CBF = COIL-BF, the coil rated point bypass factor.

WSURF = WFUNC (TSURF, 100., BLDGP) gives the 100 per cent saturation humidity ratio at the temperture TSURF and pressure BLDGP.

If the dry coil mixed air humidity ratio from Eq. (IV.64) is larger than the coil surface humidity ratio at saturation, some condensation will occur. To solve this problem, the bypass relationship in Eq. (IV.65) is used, together with Eqs. (IV.62) and (IV.63). Solving for the room air humidity ratio (WR) gives

$$WR = \frac{(CBF * PO * WMAX) + [(1.0 - CBF) * WSURF] + DW + (F * WMAX)}{1.0 + F - [CBF * (1.0 - PO)]} . \qquad (IV.66)$$

Then reappling Eqs. (IV.63) and (IV.67), below, gives the mixed air humidity ratio and the coil exit air humidity ratio.

$$WC = (CBF * WM) + [(1.0 - CBF) * WSURF]. \qquad (IV.67)$$

The total zone cooling load (QCZ) can now be calculated along with its sensible cooling component (QCSZ)

$$QCZ = [H(TMZ,WM) - H(TCZ,WC)] * \frac{<CFMAX> * 60.0}{V(TMZ,WM,BLDGP)}, \qquad (IV.68)$$

where H and V are the enthalpy and specific volume, respectively, of the air at the conditions indicated and

$$QCSZ = CONS(1) * <CFMAX> * (TMZ - TCZ). \qquad (IV.69)$$

If the COOLING-CAPACITY has not been specified, both the COOLING-CAPACITY and COOL-SH-CAP can be calculated. Note, because the above loads are not necessarily at the ARI* point (80°F indoor entering dry-bulb temperature, 67°F indoor entering wet-bulb temperature, and 95°F outdoor dry-bulb temperature), it is necessary to adjust these loads back to the ARI point to get rated equipment capacity

$$\text{COOLING-CAPACITY} = \frac{QCZ}{QCM1},$$

$$\text{COOL-SH-CAP} = \frac{QCSZ - QCM3}{QCM2} \text{ or} \qquad (IV.70)$$

$$\text{COOLING-CAPACITY, whichever is smaller,}$$

where

QCM1 = CVAL(COOL-CAP-FT,EWB,EDB) [COOL-CAP-FT is a correction function to adjust the total cooling capacity for off-rated entering wet-bulb and entering dry-bulb temperatures],

QCM2 = CVAL(COOL-SH-FT,EWB,EDB), a similar correction function but to the sensible portion of the total cooling capacity, and

QCM3 = 0.0 for SYSTEM-TYPE $\neq$ HP or PTAC, or

QCM3 = CONS(1) * $<CFMAX>$ * (1.0-CBF) * (TMZ-80.0) for SYSTEM-TYPE = HP or PTAC.

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If the user has specified COOLING-CAPACITY, the design heat extraction rate must be recalculated, given this specified capacity. If the RATED-CFM has also been specified, it is necessary to multiply both the COOLING-CAPACITY and the COOL-SH-CAP by the values of the RATED-CCAP-FCFM and RATED-SH-FCFM respectively (they are evaluated at PLRCFM = <CFMAX> / RATED-CFM. If the COOL-SH-CAP has not been specified, it is first set to the value described in Eq. (IV.70). Then the sensible cooling capacity at the peak operating condition is calculated as

$$\text{QCSF} = \text{the smaller of } [(\text{COOL-SH-CAP} * \text{QCM2}) + \text{QCM3}] \text{ and}$$

$$(\text{COOLING-CAPACITY} * \text{QCM1}). \qquad \text{(IV.71)}$$

Then, if the ASSIGNED-CFM has not been specified but the capacity was specified, <CFMAX> is recalculated. Then the maximum heat extraction rate can be calculated

$$<\text{CFMAX}> = \frac{\text{QCSF}}{\text{CONS(1)} * (\text{DESIGN-COOL-T} - \text{TCZ})}, \text{ and} \qquad \text{(IV.72)}$$

$$<\text{ERMIND}> = \text{CONS(1)} * <\text{CFMAX}> * (\text{DESIGN-COOL-T} - \text{T}), \qquad \text{(IV.73)}$$

where

$$\text{T} = \text{TMZ} - \frac{\text{QCSF}}{\text{CONS(1)} * <\text{CFMAX}>} \quad \text{or}$$

$$(\text{MIN-SUPPLY-T} - \text{SUPPLY-DELTA-T}), \text{ whichever if larger.}$$

For induction unit coils, it is assumed that the coils are dry. This assumption means that it is assumed that the central air handler air is dry enough to absorb space heat gains without exceeding the zone coil dew point temperature. The air temperature, being supplied from the central air handler, must be calculated

$$Q_{zone} = \text{COOLING-CAPACITY} = \text{CONS(1)} * <\text{CFMAX}> * (\text{TS} - \text{TCZ}).$$

$$\text{(IV.74)}$$

where

$$\text{TS} = \frac{\text{MIN-SUPPLY-T} + (\text{INDUCTION-RATIO} * \text{DESIGN-COOL-T})}{1.0 + \text{INDUCTION-RATIO}} \quad \text{and}$$

$$TCZ = DESIGN\text{-}COOL\text{-}T - \frac{<ERMAXD>}{CONS(1) * <CFMAX>} .$$

If the user has specified the COOLING-CAPACITY, only the design heat extraction rate needs to be recalculated.

$$<ERMAXD> = MAX\text{-}COOL\text{-}RATE + (COOLING\text{-}CAPACITY - Q_{zone}). \qquad (IV.75)$$

Step 5. the minimum supply air flow rate for non-zonal systems (central systems)

In systems with variable-air volume flow capability, it is necessary to calculate the minimum air flow fraction (<MINCFMR>). It is also necessary to calculate the maximum air flow for the heating mode (<CFMAXH>). For unitary or zonal systems, the minimum air flow rate fraction is always 1.0 and the maximum heating air flow rate is always equal to the design cooling air flow rate (<CFMAX>).

For systems that allow MIN-CFM-RATIO, and it has been specified, it is used as the value for <MINCFMR>. If the MIN-CFM-RATIO has not been specified, it is calculated based upon the larger of the ventilation air and exhaust air requirements. Additionally, if the THERMOSTAT-TYPE is not equal to REVERSE-ACTION, the supply air flow rate required for heating is compared to the supply air flow rate required for ventilation and exhaust

$$<MINCFMR> = \text{the larger of } \frac{<VENTMIN>}{<CFMAX>} \text{ and } \frac{EXHAUST\text{-}CFM}{<CFMAX>} \text{, or} \qquad (IV.76)$$

$$\frac{<ERMIND>}{CONS(1) * (DESIGN\text{-}HEAT\text{-}T - MAX\text{-}SUPPLY\text{-}T)} ,$$

if THERMOSTAT-TYPE = REVERSE-ACTION.

$$<CFMAXH> = <CFMAX> * <MINCFMR>\text{, or}$$

$$<CFMAX>\text{, if THERMOSTAT-TYPE = REVERSE-ACTION.} \qquad (IV.77)$$

The design heat addition rate can now be recalculated as

$$<ERMIND> = CONS(1) * <CFMAXH> * (DESIGN\text{-}HEAT\text{-}T - MAX\text{-}SUPPLY\text{-}T) \qquad (IV.78)$$

where MAX-SUPPLY-T = MIN-SUPPLY-T + REHEAT-DELTA-T, and the reheat coil capacity, which is

$$\text{<HEATCAPZ>} = \text{CONS(1)} * \text{<CFMAXH>} * \text{REHEAT-DELTA-T}. \qquad \text{(IV.79)}$$

<u>Step 6. the sum of the various quantities needed for the central air handler calculation, if present</u>

For all the various system types, it is necessary now to add the BASE-BOARD-RATING to <ERMIND> so that the total design heat addition rate is reflected in this value.

For systems with central air handlers, it is necessary to sum up the various zone quantities that will be used in the following system design calculations. These quantities include:

(1) the minimum air flow rate (CFMRM),
(2) the heating air flow rate (CFMH),
(3) the total supply air flow rate (CFM),
(4) the total exhaust air flow rate (ECFM),
(5) the average DESIGN-HEAT-T (AZHEAT),
(6) the average DESIGN-COOL-T (AZCOOL),
(7) the cooling mode return air temperature (TRMAX),
(8) the heating mode return air temperature (TRMIN),
(9) the cooling peak latent space gain (QLMAX),
(10) the heating peak latent space gain (QLMIN),
(11) the cooling peak infiltration rate (CINFMX),
(12) the heating peak infiltration rate (CINFMN),
(13) the number of supply air CFM required to produce one air change/hour (<CFM/ACH>), and
(14) the total zone air supply flow rate assigned by the user (ACFM).

$$\text{(1)} \quad \text{CFMRM} = \sum_{nz=1}^{nzones} \left(\text{<CFMAX>}_{nz} * \text{<MINCFMR>}_{nz} * \text{MULTIPLIER}_{nz} \right), \qquad \text{(IV.80)}$$

$$\text{(2)} \quad \text{CFMH} = \sum_{nz=1}^{nzones} \frac{\text{<CFMAXH>}_{nz} * \text{MULTIPLIER}_{nz}}{\text{DALINR}}, \qquad \text{(IV.81)}$$

where DALINR = (1.0 - DUCT-AIR-LOSS) * (1.0 + INDUCTION-RATIO),

(3) $$CFM = \sum_{nz=1}^{nzones} \frac{<CFMAXH> * MULTIPLIER_{nz}}{DALINR}, \qquad (IV.82)$$

(4) $$ECFM = \sum_{nz=1}^{nzones} \left(EXHAUST\text{-}CFM * MULTIPLIER_{nz}\right), \qquad (IV.83)$$

(5) $$AZHEAT = \frac{\sum_{nz=1}^{nzones} \left(DESIGN\text{-}HEAT\text{-}T * <CFMAX> * MULTIPLIER_{nz}\right)}{CFM * DALINR}, \qquad (IV.84)$$

(6) $$AZCOOL = \frac{\sum_{nz=1}^{nzones} \left(DESIGN\text{-}COOL\text{-}T * <CFMAX> * MULTIPLIER_{nz}\right)}{CFM * DALINR}, \qquad (IV.85)$$

(7) $$TRMAX = \frac{\sum_{nz=1}^{nzones} \left[(<CFMAX> - EXHAUST\text{-}CFM_{nz}) * DESIGN\text{-}COOL\text{-}T + \frac{<QPPEAKC>}{CONS(1)}\right] * ZMULT}{(CFMH - ECFM) * DALINR}$$

$$+ \sum_{np=1}^{nplenums} \frac{<QMAX>_{np} * ZMULT_{np}}{CONS(1) * (CFMH - ECFM) * DALINR}, \qquad (IV.86)$$

(8) $$TRMIN = \frac{\sum_{nz=1}^{nzones} \left[(<CFMAX> - EXHAUST\text{-}CFM_{nz}) * DESIGN\text{-}HEAT\text{-}T + \frac{<QPPEAKH>}{CONS(1)}\right] * ZMULT}{(CFMH - ECFM) * DALINR}$$

$$+ \sum_{np=1}^{nplenums} \frac{<QMIN>_{np} * ZMULT_{np}}{CONS(1) * (CFMH - ECFM) * DALINR}, \qquad (IV.87)$$

(9) $$QLMAX = \sum_{nz=1}^{nzones} \left(\langle QLPEAKC \rangle_{nz} * MULTIPLIER_{nz} * RETR_{nz} \right), \qquad (IV.88)$$

where

$$RETR_{nz} = 1.0 - \frac{EXHAUST\text{-}CFM_{nz}}{\langle CFMAX \rangle_{nz}},$$

(10) $$QLMIN = \sum_{nz=1}^{nzones} \left(\langle QLPEAKH \rangle_{nz} * MULTIPLIER_{nz} * RETR_{nz} \right), \qquad (IV.89)$$

(11) $$CINFMX = \sum_{nz=1}^{nzones} \left(\langle CFMIPEAKC \rangle_{nz} * MULTIPLIER_{nz} * RETR_{nz} \right), \qquad (IV.90)$$

(12) $$CINFMN = \sum_{nz=1}^{nzones} \left(\langle CFMIPEAKH \rangle_{nz} * MULTIPLIER_{nz} * RETR_{nz} \right), \qquad (IV.91)$$

(13) $$\langle CFM/ACH \rangle = \sum_{nz=1}^{nzones} \left(\langle VOLUME \rangle_{nz} * MULTIPLIER_{nz} \right), \text{ and} \qquad (IV.92)$$

(14) $$ACFM = \sum_{nz=1}^{nzones} \left(ASSIGNED\text{-}CFM_{nz} * MULTIPLIER_{nz} \right). \qquad (IV.93)$$

D. Calculate the supply air flow rate for the coincident-sized supply fan, if present.

If the type of system selected by the user allows a variable-air volume fan, the design flow rate of this fan may be specified based upon the coincident building peak load rather than upon the sum of the design flow rates of all zones (non-coincident peak). The program can size the fan automatically based upon the larger of the building cooling or heating peaks, as calculated by the LOADS program. Because only one set of these peaks is calculated for the sum of all SPACEs, it is required that this be the only SYSTEM in the PLANT-ASSIGNMENT instruction. The following conditions must all be satisfied:

(1) Only one SYSTEM is in this PLANT-ASSIGNMENT,
(2) the user has not specified SUPPLY-CFM,
(3) SIZING-OPTION is equal to COINCIDENT, and
(4) the MIN-CFM-RATIO is less than 1.0.

If all these conditions are satisfied, CFM is calculated based upon the building coincident heating and cooling peaks (BLDGQH and BLDGQC respectively); the greater peak determines the value of CFM.

$$CFM = \frac{BLDGQH}{CONS(1) * (AZHEAT - MAX\text{-}SUPPLY\text{-}T) * DALINR}$$

or

$$CFM = \frac{BLDGQC}{CONS(1) * (AZCOOL - MIN\text{-}SUPPLY\text{-}T) * DALINR} , \qquad (IV.94)$$

where DALINR = (1.0 - DUCT-AIR-LOSS) * (1.0 + INDUCTION-RATIO).

If the user has not specified a value for SUPPLY-CFM, it is set equal to the value either calculated by Eq. (IV.82) if SIZING-OPTION = NON-COINCIDENT or Eq. (IV.94) if SIZING-OPTION = COINCIDENT (see the SYSTEM instruction). The value for MIN-OUTSIDE-AIR is set to OUTA / SUPPLY-CFM, where OUTA is calculated by Eq. (IV.95)

$$OUTA = \sum_{nz=1}^{nzones} \left(\langle VENTMIN \rangle_{nz} * MULTIPLIER_{nz} \right) . \qquad (IV.95)$$

E. Adjust each program-calculated zone supply air flow rate, heating rate, and cooling rate for a user-specified central air handler fan size.

If the user has specified a value for SUPPLY-CFM, the zone supply air flow rates must add up to equal the user-specified value of SUPPLY-CFM. This means that the difference between the sum of the ASSIGNED-CFMs (ACFM) at the zone level and the SUPPLY-CFM at the system level must be redistributed. This redistribution is done only if (1) the specified SUPPLY-CFM is not equal to CFM from Eq. (IV.82) or (IV.94) and (2) this calculated CFM minus the sum of the ASSIGNED-CFMs (ACFM) is greater than zero. Any remaining unassigned flow is then assigned to the zones without a specified value for ASSIGNED-CFM in proportion to their design calculated air flow rate requirements

$$R = \frac{[\text{SUPPLY-CFM} * (1.0 - \text{DUCT-AIR-LOSS})] - \text{ACFM}}{[\text{CFM} * (1.0 - \text{DUCT-AIR-LOSS})] - \text{ACFM}} . \qquad \text{(IV.96)}$$

The program recalculates, for each zone in this system that did not have an ASSIGNED-CFM specified, the following quantities

<CFMAX>	multiply by R,
<MINCFMR>	divide by R,
<CFMAXH>	equal to <CFMAX> if THERMOSTAT-TYPE = REVERSE-ACTION, otherwise, <CFMAX> * <MINCFMR>,
<ERMAXD>	multiply by ratio of new/old values of <CFMAX>,
<ERMIND>	multiply by ratio of new/old values of <CFMAX>, and
<HEATCAPZ>	multiply by ratio of new/old values of <CFMAX> if REHEAT-DELTA-T $\neq$ 0.0.

If this is an induction system, it is necessary to recalculate the coil capacities described earlier. CFMH and CFMRM must also be recalculated.

F. Calculate the capacity of the central air handler heating coil.

For systems with a central air handler, the heating coil capacity must now be calculated. First, the mixed air temperature is calculated by knowing the fraction (PO) of outside ventilation air in the total supply air flow rate. For cooling that fraction is,

$$\text{PO} = \text{the larger of MIN-OUTSIDE-AIR and } \frac{\text{ECFM}}{\text{SUPPLY-CFM}} \qquad \text{(IV.97)}$$

and for heating, the same outside air flow rate must be considered, but possibly at a different total supply air flow rate

$$\text{POH} = \text{PO} * \frac{\text{SUPPLY-CFM}}{\text{CFMH}}. \qquad \text{(IV.98)}$$

Thus, the heating and cooling mixed air temperatures (TMIN and TMAX respectively) can be calculated

$$\text{TMIN} = (\text{POH} * \text{DBTMIN}) + [(1.0 - \text{POH}) * \text{TRMIN}] \qquad \text{(IV.99)}$$

(however, if FAN-PLACEMENT = BLOW-THROUGH, TMIN = (POH * DBTMIN) + [(1.0 - POH) * TRMIN] + SUPPLY-DELTA-T)

$$\text{TMAX} = (\text{PO} * \text{DBTMAX}) + [(1.0 - \text{PO}) * \text{TRMAX}] \qquad \text{(IV.100)}$$

(however, if FAN-PLACEMENT = BLOW-THROUGH, TMAX = (PO * DBTMAX) + [(1.0 - PO) * TRMAX] + SUPPLY-DELTA-T).

The design heating supply air temperature (TH) is set to HEAT-SET-T. If this value has not been specified, the value of TH is determined as follows

TH = MIN-SUPPLY-T, if SYSTEM-TYPE = TPIU or FPIU, or

TH = MAX-SUPPLY-T, if SYSTEM-TYPE = HVSYS (with HEAT-CONTROL $\neq$ CONSTANT), RESYS, SZRH, PSZ, MZS, DDS, or PMZS, or

TH = the average DESIGN-HEAT-T for SYSTEM-TYPE = HVSYS (with HEAT-CONTROL = CONSTANT), or

TH = PREHEAT-T, for all other SYSTEM-TYPEs. (IV.101)

All the above, except the last, are adjusted by subtracting the air stream temperature rise caused by fan heat and adding the duct temperature loss to get the actual required heating coil exit temperature. The mixed air temperature is determined by Eq. (IV.99), or Eq. (IV.100) if the SYSTEM-TYPE is MZS, DDS, or PMZS and OA-CONTROL $\neq$ FIXED. In this case,

TMIN = the smaller of the value calculated by Eq. (IV.99) and

(MIN-SUPPLY-T - DUCT-DELTA-T). (IV.102)

If the resulting value of TMIN is less than the PREHEAT-T, TMIN = PREHEAT-T. The sensible heating capacity can now be calculated

QH = CONS(1) * CFMH * (TMIN - TH). (IV.103)

If the HEATING-CAPACITY has not been specified by the user, it can be calculated from Eq. (IV.104)

$$\text{HEATING-CAPACITY} = \frac{\text{QH}}{\text{QHM1}}, \qquad \text{(IV.104)}$$

where

QHM1 = 1.0 if HEAT-SOURCE $\neq$ HEAT-PUMP

but if HEAT-SOURCE = HEAT-PUMP,

QHM1 = CVAL(HEAT-CAP-FT,DBT,TMIN), [HEAT-CAP-FT is a correction function to adjust the total heating capacity for off-rated outdoor dry-bulb temperature and entering mixed air temperature]

with

DBT = the larger of DBTMIN and MIN-HP-T.

If the HEAT-SOURCE $\neq$ HEAT-PUMP and ELEC-HEAT-CAP has not been specified, it (ELECT-HEAT-CAP) is set to QH as calculated in Eq. (IV.103).

If the HEATING-CAPACITY <u>has</u> been specified by the user, then it may not be possible to obtain the desired heating supply air temperature. Thus, using the specified heating capacity, the obtainable supply air temperature is calculated and then the design heat addition rate is adjusted for each zone to reflect the available heating capacity. The supply air temperature obtainable (QHT) is

$$\text{QHT} = \text{TMIN} + \frac{\text{HEATING-CAPACITY} * \text{QHM1}}{[\text{CONS}(1) * \text{CFMH}]} + \text{SUPPLY-DELTA-T}$$

$$- \text{DUCT-DELTA-T} + \text{REHEAT-DELTA-T} \qquad \text{(IV.105)}$$

or MAX-SUPPLY-T, whichever is smaller.

The maximum heat addition rate and the zone coil heating capacity are recalculated for each conditioned zone, if this is not an induction system.

$$\langle \text{ERMIND} \rangle_{nz} = \text{BASEBOARD-RATING}_{nz} + [\text{CONS}(1)$$

$$* \langle \text{CFMAXH} \rangle_{nz} * (\text{DESIGN-HEAT-T}_{nz} - \text{QHT})], \text{ and} \qquad \text{(IV.106)}$$

$$\text{HEATING-CAPACITY}_{nz} = \text{CONS}(1) * \langle \text{CFMAXH} \rangle_{nz} * \text{REHEAT-DELTA-T}. \qquad \text{(IV.107)}$$

G. Calculate the capacity of the central air handler cooling coil.

The central cooling coil capacity calculation proceeds in a manner similar to that already discussed for zonal units. It is necessary to calculate both the sensible cooling and latent cooling components of the design load

$$Q_{total} = Q_{sensible} + Q_{latent}. \qquad \text{(IV.108)}$$

The sensible cooling component is calculated in a manner similar to the heating capacity calculation

$$Q_{sensible} = \frac{\text{COOL-SH-CAP} - \text{QCM3}}{\text{QCM2}} = \text{CONS(1)} * \text{SUPPLY-CFM} * (\text{TMAX} - \text{TC}), \tag{IV.109}$$

where

QCM2 = CVAL(COOL-SH-CAP,EWB,EDB)
[COOL-SH-CAP is a correction function to the sensible cooling capacity (COOL-SH-CAP) to adjust for off-rated entering wet-bulb and entering dry-bulb temperatures],

EWB = coil entering wet-bulb temperature,

EDB = TMAX (DBTMAX for SYSTEM-TYPE = RESYS, PSZ, PVAVS, or PMZS), or COOL-FT-MIN, whichever if larger,

TMAX is as defined in Eq. (IV.100),

TC = MIN-SUPPLY-T - DUCT-DELTA-T (however, if FAN-PLACEMENT = DRAW-THROUGH, TC = MIN-SUPPLY-T - DUCT-DELTA-T - SUPPLY-DELTA-T) and,

QCM3 = CONS(1) * <SUPPLY-CFM> * (1.0 - COIL-BF) * (TMZ - 80.0) for SYSTEM-TYPE = PMZS, PSZ, and PVAVS (the off-design space dry-bulb temperature adjustment) or 0.0 for other SYSTEM-TYPEs.

To calculate QCM2 requires knowing the wet-bulb temperature, thus, the moisture balance is solved first. As in Eqs. (IV.61) and (IV.62),

$$\text{WR} = \frac{\text{WC} + \text{DW} + (\text{F} * \text{WMAX})}{1.0 + \text{F}}, \tag{IV.110}$$

where

$$\text{F} = \frac{\text{CINFMX}}{\text{SUPPLY-CFM}}, \text{ and}$$

$$\text{DW} = \frac{\text{QLMAX}}{\text{CONS(2)} * \text{RCFM}}.$$

For a dry coil it is possible to use Eq. (IV.64). For a wet coil [that is, WM in Eq. (IV.64) is larger than WSURF in Eq. (IV.65)], it is possible to use TC and TMAX in place of TCZ and TMZ and get the same relationship as Eq. (IV.66). Thus, the total and sensible cooling loads are calculated as

$$QC_{total} = \frac{[H(TMAX,WM) - H(TC,WC)] * SUPPLY\text{-}CFM * 60.0}{V(TMAX,WM,BLDGP)} ,$$

where H and V are the enthalpy and specific volume of the air, respectively, at the conditions indicated and

$$QCS = CONS(1) * SUPPLY\text{-}CFM * (TMAX - TC). \qquad (IV.111)$$

If the COOLING-CAPACITY has not been specified, both the COOLING-CAPACITY and COOL-SH-CAP can be calculated as in Eq. (IV.70). If COOLING-CAPACITY has been specified, it is necessary to recalculate the obtainable supply air temperature and then for each zone change the design heat extraction rate. If the RATED-CFM has also been defined, it is necessary to multiply COOLING-CAPACITY, COOL-SH-CAP, and COOLING-EIR by the values of RATED-CCAP-FCFM, RATED-SH-FCFM, and RATED-CEIR-FCFM, respectively (evaluated at PLRCFM = SUPPLY-CFM / RATED-CFM). If the COOL-SH-CAP has not been specified, it can be calculated by Eq. (IV.70). Then QCSF (the sensible cooling capacity at the peak operating condition) is calculated as in Eq. (IV.71) and the minimum supply air temperature (QCT) is calculated as

$$QCT = TMAX - \frac{QCSF}{CONS(1) * SUPPLY\text{-}CFM} + DUCT\text{-}DELTA\text{-}T \qquad (IV.112)$$

(however, if FAN-PLACEMENT = DRAW-THROUGH, add, to the right-hand side of Eq. (IV.112), SUPPLY-DELTA-T or MIN-SUPPLY-T, whichever is larger).

Then, the maximum heat extraction rate is recalculated for all zones in non-induction systems.

$$<ERMAXD> = CONS(1) * <CFMAX> * (DESIGN\text{-}COOL\text{-}T - QCT). \qquad (IV.113)$$

If the user has not specified the SYSTEM level MIN-CFM-RATIO, it must be calculated

$$\text{MIN-CFM-RATIO}_{\text{system}} = \frac{\text{CFMRM}}{\text{SUPPLY-CFM} * \text{DALINR}} , \qquad (\text{IV.114})$$

where DALINR = (1.0 - DUCT-AIR-LOSS) * (1 + INDUCTION-RATIO).

3. SYSTEM SIMULATION ROUTINES

3.1 Central Air-Handler Simulations

3.1.1 Single-Duct System Simulation for SYSTEM-TYPE = PSZ, PVAVS, SZRH, VAVS, or CBVAV (subroutines VARVOL and SDSF)

These subroutines simulate the heat and moisture exchange in systems that use a single-duct air-handling unit. This includes packaged systems [single-zone (PSZ) and variable-air volume (PVAVS)], and central or built-up systems, [single-zone reheat (SZRH), variable-air volume (VAVS), and ceiling bypass variable-air volume (CBVAV)]. Induction systems are described separately in this chapter. The simulation of these single-duct air-handling systems uses general utility subroutines, described later, such as the supply air temperature calculation (subroutine DKTEMP), the room air temperature and heat addition/extraction rate calculation (subroutine TEMDEV), the outside ventilation air calculation (subroutine ECONO), and the fan energy consumption calculation (subroutine FANPWR). The main calculation for these simulations is divided into two parts: (1) the zone air terminal calculation (subroutine VARVOL) and (2) the single-duct air-handler calculation (subroutine SDSF). The latter subroutine is used for the simulation of fan coils and induction systems, in addition to those already mentioned. These system subroutines are described separately in this manual.

Calculation Outline

I. Zone Air Terminal Calculation (subroutine VARVOL)

A. For VAV systems, calculate the maximum supply air CFM ratio allowed for the zones this hour.

B. Calculate the supply air temperature (subroutine DKTEMP).

C. For each zone attached to this system,

1. calculate the maximum cooling and heating rates,
2. calculate the hourly zone temperature and the hourly cooling and heating rates (subroutine TEMDEV),
3. calculate the supply air CFM, the reheat energy, and the baseboard input energy, and
4. sum the infiltration air, the latent heat gain, the supply air CFM, the exhaust air cfm, the electrical consumption, and other quantities.

D. Calculate the return air flow rate and temperature.

E. Save all quantities that would be needed for a solar system simulation.

II. Single-Duct Air-Handler Simulation (subroutine SDSF)

See Sec. IV.3.1.2.

Calculation Algorithms

I. Zone Air Terminal Calculation (subroutine VARVOL)

A. For VAV systems, calculate the maximum supply air CFM ratio allowed for the zones this hour.

If the system being simulated has air terminal boxes that have a variable air volume control capability, the amount of air that can be passed into each zone can vary between some fixed minimum fraction (MIN-CFM-RATIO) of the design air flow rate and a maximum flow rate that depends upon the flow into the rest of the zones, but has an upper limit of the zone design flow rate. This maximum flow rate may vary because although the volume control of the box may be wide open, the system fan may not be able to provide the design air flow rate because many of the other zone boxes are also wide open. If and when this occurs, it is because the fan SUPPLY-CFM times the MAX-FAN-RATIO is less than the sum of all the zone design flow rates.

Thus, if the average MIN-CFM-RATIO is less than 1.0 for this system (indicating a variable-air volume system), and either (1) the supply air fan was off the preceding hour or (2) the supply air fan CFM for the preceding hour (<PASTCFM>) was greater than SUPPLY-CFM, calculate

$$\mathrm{CFMRAT} = \frac{\mathrm{SUPPLY\text{-}CFM} * \mathrm{MAX\text{-}FAN\text{-}RATIO} * (1.0 - \mathrm{DUCT\text{-}AIR\text{-}LOSS})}{\sum_{nz=1}^{nzones} (\langle \mathrm{CFMAX} \rangle_{nz} * \mathrm{MULTIPLIER}_{nz})}, \qquad \text{(IV.115)}$$

otherwise, CFMRAT is set equal to 1.0.

B. Calculate the supply air temperature (subroutine DKTEMP).

DKTEMP is called to calculate the maximum and minimum supply air temperatures (THMAX and TCMIN) for single-zone single-duct systems (SZRH and PSZ), as well as the supply air temperature (TC) for other single-duct systems.

C. For each zone attached to this system, calculate the performance of the equipment in the zone, as well as the zone conditions.

1. Calculate the maximum heat extraction and heat addition rates for the zone. This estimate will be done by using the zone temperature for the end of the previous hour and the supply air temperature. The maximum cooling (heat extraction) rate is

$$\langle \mathrm{ERMAX} \rangle = \mathrm{CONS}(1) * \langle \mathrm{CFMAX} \rangle * \mathrm{CFMRAT} * (\langle \mathrm{TNOW} \rangle - \mathrm{TCMINZ}) \qquad \text{(IV.116)}$$

and the maximum heating (heat addition) rate is

$$<ERMIN> = CONS(1) * CFMH * (<TNOW> - THMAXZ) \qquad (IV.117)$$

where

TCMINZ = minimum zone supply air temperature (TCMIN from subroutine DKTEMP for single zone systems and TC from subroutine DKTEMP for other single-duct systems),

THMAXZ = maximum supply air temperature [THMAX for single zone systems and (TC + REHEAT-DELTA-T) for other single-duct systems], and

CFMH = the smaller of <CFMAXH>, which is the heating CFM, and (<CFMAX> * CFMRAT).

In addition, it is necessary to know the heat extraction rate when the zone temperature is within the dead band of the thermostat. In this case, the air flow rate will be at the minimum and no reheat will be supplied. The minimum air flow rate is

$$CFMIN = (<CFMAX> * MIN\text{-}CFM\text{-}RATIO) \text{ or } (<CFMAX> * CFMRAT) \qquad (IV.118)$$

whichever is smaller, and the minimum cooling rate can be calculated as

$$ERMAXM = CONS(1) * CFMIN * (<TNOW> - TM) \qquad (IV.119)$$

where TM = TPOMIN, which is the mixed air temperature at the minimum outside air damper position, for single zone systems and TM = TC for other single-duct systems.

2. Next, subroutine TEMDEV is called to calculate the current hour's zone temperature and the cooling and heating rates. TEMDEV will correct the previously calculated maximum cooling and heating rates for the zone temperature change during the hour. The average zone temperature for the current hour (TAVE) is calculated as

$$TAVE = \frac{<TNOW> + <TPAST>}{2.0} .$$

This is the temperature that will be used for all zone coil load calculations.

3. The supply air flow rate, the reheat energy, and the baseboard energy are now calculated for each zone. For single zone systems, with or without subzones, the supply air temperature (TC) of the control zone (first zone specified) needs to be calculated; that is,

$$TC = TAVE - \left(\frac{<QNOW>}{CONS(1) * <CFMAX>}\right). \qquad (IV.120)$$

This value for TC is not allowed to go below TCMIN (the minimum supply air temperature of the air handler) or above THMAX (the maximum supply air temperature of the air handler). If the zone temperature is within the thermostat dead band, untreated mixed air is delivered into the zone (and subzones, if present). Thus, TC is recalculated as

$$\begin{aligned} TC = (POMIN * DBT) + \Big\{(1.0 - POMIN) * [TAVE + (<RETURN\text{-}DELTA\text{-}T> \\ * CONS(3))]\Big\} + DUCT\text{-}DELTA\text{-}T + [SUPPLY\text{-}DELTA\text{-}T * CONS(3)]. \end{aligned} \qquad (IV.121)$$

In either case, the zone air flow rate (CFMZ) is set to the design air flow rate of <CFMAX>.

If this is not a single zone system, or not the control zone of a single zone system with subzones, it is necessary to calculate the air flow rates to the zones and any zone reheat coil energies, if such coils were specified. If the zone temperature is within the dead band of the thermostat, the zone air flow rate (CFMZ) is set to the minimum (CFMIN).

If the heat extraction/addition rate (<QNOW>) is greater than or equal to zero, the system is in the net cooling mode. The average zone air flow rate (ZCFM) is calculated first, using the heat extraction rate,

$$ZCFM = \frac{<QNOW>}{CONS(1) * (TAVE - TC)} . \qquad (IV.122)$$

The program then ensures that ZCFM does not exceed the maximum air flow rate (<CFMAX> * CFMRAT). The zone air flow rate (CFMZ) is then set to the larger of ZCFM as calculated in Eq. (IV.122) and CFMIN, which is the minimum air flow rate. If the value of ZCFM calculated from Eq. (IV.122) is greater than the minimum air flow rate (CFMIN), or no reheat coil is present, no reheat energy needs to be calculated. If this is not true, the reheat coil energy is calculated as

$$ZQHR = ZQH = (CFMZ - ZCFM) * CONS(1) * (TC - TAVE). \qquad (IV.123)$$

When the heat extraction/addition rate (<QNOW>) is less than zero, the system is in the net heating mode. The average air flow rate (ZCFM), based upon heat addition, is again calculated

$$ZCFM = \frac{<QNOW>}{CONS(1) * [TAVE - (TC + REHEAT\text{-}DELTA\text{-}T)]} \cdot \qquad (IV.124)$$

The program then ensures that ZCFM is not greater than the maximum air flow rate (<CFMAX> * CFMRAT) and the maximum heating air flow rate (<CFMAXH>). The zone air flow rate (CFMZ) is then set to the larger of ZCFM as calculated by Eq. (IV.124) and CFMIN, which is the minimum air flow rate. If the zone temperature is above the heating throttling range, or no reheat is possible, no reheat energy needs to be calculated. Otherwise, the reheat energy is calculated in two portions. The first portion represents the energy required to move the supply air temperature up to the average zone temperature,

$$ZQHR = CFMZ * CONS(1) * (TC - TAVE). \qquad (IV.125)$$

The second portion is the zone net heat addition rate (<QNOW>). The total reheat energy (ZQH) is calculated as the sum of ZQHR as calculated by Eq. (IV.125) and the zone net heat addition rate,

$$ZQH = ZQHR + <QNOW>. \qquad (IV.126)$$

The contribution of the baseboard heaters (QHBZ) to the reheat energy can be calculated as the larger of the reheat load (ZQH) and the baseboard heating capacity (BASEBOARD-RATING). Both quantities are negative.

4. To obtain system level performance data, several quantities need to be summed over all the zones. These include exhaust air cfm,

$$ECFM = \sum_{nz=1}^{nzones} EXHAUST\text{-}CFM_{nz} * MULTIPLIER_{nz}, \qquad (IV.127)$$

exhaust fan energy consumption,

$$FANKW = \sum_{nz=1}^{nzones} EXHAUST\text{-}KW_{nz} * MULTIPLIER_{nz}, \quad (IV.128)$$

baseboard heater energy consumption,

$$QHB = \sum_{nz=1}^{nzones} QHBZ_{nz} * MULTIPLIER_{nz}, \quad (IV.129)$$

total reheat coil energy consumption,

$$QHZ = \sum_{nz=1}^{nzones} ZQH_{nz} * MULTIPLIER_{nz}, \quad (IV.130)$$

total electrical energy consumption,

$$<SKW> = \sum_{nz=1}^{nzones} (<ZKW>_{nz} + EXHAUST\text{-}KW_{nz}) * MULTIPLIER_{nz} , \quad (IV.131)$$

heat of lights that are vented to the return air plenum,

$$QPSUM = \sum_{nz=1}^{nzones} <QP>_{nz} * MULTIPLIER_{nz}, \quad (IV.132)$$

infiltration air,

$$CINF = \sum_{nz=1}^{nzones} <CFMINF>_{nz} * RETR_{nz} * MULTIPLIER_{nz} \quad (IV.133)$$

$$\text{where } RETR_{nz} = \left(1.0 - \frac{EXHAUST\text{-}CFM_{nz}}{CFMZ_{nz}}\right),$$

and latent heat gain,

$$QLSUM = \sum_{nz=1}^{nzones} \langle QL \rangle_{nz} * RETR_{nz} * MULTIPLIER_{nz} \quad . \tag{IV.134}$$

D. Calculate the return air flow rate and temperature.

The return air temperature and the total supply air flow rate for the ceiling bypass systems are calculated differently than for all other single-duct system types. For the ceiling bypass system, the total system supply air flow rate is constant and the air that is not required by the zones is bypassed around the zones through the return air plenum. The total system supply air flow rate is calculated as

$$CFM = \sum_{nz=1}^{nzones} \langle CFMAX \rangle_{nz} * MULTIPLIER_{nz} \tag{IV.135}$$

and the return air flow rate RCFM = CFM - ECFM.

The return air temperature is calculated as

$$TR = \sum_{nz=1}^{nzones} \Big\{ TAVE_{nz} * (CFMZ_{nz} - EXHAUST\text{-}CFM_{nz}) + TC * [\langle CFMAX \rangle_{nz}$$

$$- (CFMZ_{nz} + EXHAUST\text{-}CFM_{nz})] \Big\} * \frac{MULTIPLIER_{nz}}{CFM - ECFM} \quad . \tag{IV.136}$$

For other single-duct system types (non-ceiling bypass), the return air temperature is calculated as

$$TR = \frac{\sum_{nz=1}^{nzones} TAVE_{nz} * (CFMZ_{nz} - EXHAUST\text{-}CFM_{nz}) * MULTIPLIER_{nz}}{CFM - ECFM} \qquad (IV.137)$$

where the total system supply air flow rate (CFM) is calculated from Eq. (IV.135) with $CFMZ_{nz}$ substituted for $<CFMAX>_{nz}$.

E. Save all quantitites that would be needed for a solar system simulation.

If the user specified SOLAR/HOT-WATER as an energy source for any of the coils (see SYSTEM instruction), information must be collected and passed to the PLANT program to aid in the simulation of solar system components.

The specification of ZONE-HEAT-SOURCE = SOLAR/HOT-WATER causes the program to calculate, at the SYSTEM level, the total of the zone coil loads (QHZP), the total of the zone coil air flow rates (CFMZP), and the average zone coil entering temperature (TZP). These are calculated as

$$QHZP = \sum_{nz=1}^{nzones} \left(ZQH_{nz} * MULTIPLIER_{nz}\right), \qquad (IV.138)$$

$$CFMZP = \sum_{nz=1}^{nzones} \left(CFMZ_{nz} * MULTIPLIER_{nz}\right), \text{ and} \qquad (IV.139)$$

$$TZP = \frac{\sum_{nz=1}^{nzones} \left(TC * CFMZ_{nz} * MULTIPLIER_{nz}\right)}{CFMZP}. \qquad (IV.140)$$

The specification of HEAT-SOURCE = SOLAR/HOT-WATER causes the program to calculate, at the PLANT level, the total of the central heating coil loads (QHMP), the total of the air flow rates (CFMP), and the average coil entering air temperature (TMP) for all systems in the PLANT-ASSIGNMENT instruction for which HEAT-SOURCE = SOLAR/HOT-WATER is specified. These quantities are calculated as

$$QHMP = \sum_{ns=1}^{nsystems} QH_{ns} , \qquad (IV.141)$$

$$CFMP = \sum_{ns=1}^{nsystems} CFM_{ns} \text{ , and} \tag{IV.142}$$

$$TMP = \frac{\sum_{ns=1}^{nsystems} \left(TM_{ns} * CFM_{ns} \right)}{CFMP} . \tag{IV.143}$$

Similarly, for PREHEAT-SOURCE = SOLAR/HOT-WATER, the program calculates the total of the preheat loads for all systems in the PLANT-ASSIGNMENT instruction,

$$QHPP = \sum_{ns=1}^{nsystems} QHP_{ns} \tag{IV.144}$$

and the total of the outside ventilation air flow rates for all systems in the PLANT-ASSIGNMENT instruction,

$$CFMPP = \sum_{ns=1}^{nsystems} PO_{ns} * CFM_{ns}, \tag{IV.145}$$

where PO_{ns} is the fraction of outside ventilation air flow in the total supply air flow for the system (CFM_{ns}).

3.1.2. Single-Duct Air-Handler Simulation (subroutine SDSF)

The subroutine SDSF is called to calculate the performance of equipment in the central air handling unit, as well as the plenum heat exchange and the return air fan performance.

Calculation Outline

A. Adjust the supply air CFM for duct air losses and calculate the minimum outside air fraction.

B. Calculate the fan electrical energy consumption and the fan heat addition to the air stream (subroutine FANPWR).

C. Adjust the return air temperature for plenum effects.

D. Calculate the mixed air temperature (subroutine ECONO).

E. Calculate the preheat energy.

F. If the system is in the heating mode, calculate the return air humidity ratio. If the return air humidity ratio is greater than the specified minimum, calculate the sensible heating. If the return air humidity ratio is less than the specified minimum, calculate the sensible heating load and, in addition, the humidification heating load.

G. If the system is in the cooling mode, calculate the coil surface temperature and saturation humidity ratio. Then calculate the mixed air humidity ratio, assuming a dry coil. If the mixed air humidity ratio is less than the coil surface humidity ratio at saturation, calculate the sensible cooling energy. If the mixed air humidity ratio is larger than the coil surface humidity ratio at saturation, recalculate the mixed air humidity ratio, the coil exit humidity ratio, and the return air humidity ratio, assuming a wet coil. If the return air humidity ratio is larger than the specified maximum, depress the coil operating temperature to obtain humidity control. Then calculate the sensible and latent components of the cooling load.

H. Calculate the cooling part load ratio.

I. If the cooling is accomplished by direct expansion,

   1. calculate the outside (condenser) fan energy consumption and
   2. calculate the compressor energy consumption.

Calculation Algorithms

A. Adjust the supply air CFM for duct air losses and calculate the minimum outside air fraction.

The total supply air flow rate is calculated by adjusting the sum of the zone air flow rates for DUCT-AIR-LOSS. The minimum ratio (POM) of outside ventilation air flow rate to total supply air flow rate is calculated by using either the MIN-OUTSIDE-AIR value or the value referenced by

MIN-AIR-SCH for the current hour, if it has been specified. The MIN-AIR-SCH value will take precedence if it has been specified. In addition, if the total of the zone exhaust air flow rates is larger than the value just described, that total is used as the minimum outside air flow rate.

B. Calculate the fan electrical energy consumption and the fan heat addition to the air stream (subroutine FANPWR).

The subroutine FANPWR is called to calculate the electric energy inputs (SFKW and RFKW) to the supply air and return air fans. This subroutine will also determine the ratio of this hour's fan heat gain to the design fan heat gain for the supply air and return air fans (DTS and DTR).

C. Adjust the return air temperature for plenum effects.

The effect of heat from lights (that are vented to the return air plenum) on the return air stream and the interaction between the return air and plenum spaces needs to be calculated next. The temperature rise of the return air stream caused by heat from lights, specified in LOADS, is

$$DTP = \frac{QPSUM}{CONS(1) * RCFM} . \tag{IV.146}$$

The effect of plenum heat exchange for each zone is calculated by subroutine TEMDEV. The total effect of all plenums on the entire return air stream temperature is calculated by using the MULTIPLIER weighted average of all the plenums. Thus, the relationship of the temperature rise (TRA) and the total heat exchange between the plenums is expressed as

$$TRA = \frac{\sum_{np=1}^{nplenums} \langle QNOW \rangle_{np} * MULTIPLIER_{np}}{CONS(1) * RCFM} \tag{IV.147}$$

where $\langle QNOW \rangle_{np}$ is the heat exchanged with the plenum, as calculated by subroutine TEMDEV, and RCFM = CFM − ECFM.

D. Calculate the mixed air temperature (subroutine ECONO).

The supply air temperature (TC) is adjusted for DUCT-DELTA-T. If the supply air temperature is less than or equal to the return air temperature (that is, the cooling mode), the supply air temperature is lowered by DUCT-DELTA-T. Otherwise (in the heating mode), the supply air temperature is raised by that amount. This means extra cooling or heating, respectively, needs to be done, to compensate for heat gain or loss in the ductwork.

The mixed air controller set point temperature is determined by subtracting, from TC, the air stream temperature rise caused by supply fan heat gain,

SUPPLY-DELTA-T * DTS.

The final return air temperature is found by adding the return air stream temperature rise, caused by return fan heat gain, to the exit weighted plenum air temperature. The return air stream temperature rise, caused by return fan heat gain, is calculated as

RETURN-DELTA-T * DTR.

The subroutine ECONO is then called to calculate the mixed air temperature (TM) and the fraction (PO) of outside ventilation air flow in the mixed air flow.

E. Calculate the preheat energy.

If the mixed air temperature is less than the PREHEAT-T, and heating is available, the preheat energy is calculated as

$$QHP = CONS(1) * CFM * (TM - PREHEAT\text{-}T), \tag{IV.148}$$

and the mixed air temperature is reset to the PREHEAT-T. The mixed air stream temperature (TM) is then increased by the temperature rise, caused by supply fan heat gain, if FAN-PLACEMENT was equal to BLOW-THROUGH.

F. If the system is in the heating mode, calculate the return air humidity ratio, the mixed air humidity ratio, the sensible heating energy, and the humidification heating energy.

If the coil entering air temperature (TM) is less than the coil exit air temperature (TC) the air handler is in the net heating mode. To see if humidification is necessary, a moisture balance on the entire system is performed, equating gains with losses

$$(CFM * WR) + (CINF * WR) = (CFM * WCOIL) + (CINF * HUMRAT) + \Delta W \tag{IV.149}$$

where

WR = the return air humidity ratio,
HUMRAT = the outdoor humidity ratio,
WCOIL = the supply air humidity ratio, and

$\Delta W = \frac{QLSUM}{CONS(2)}$, the latent heat gain in the return air, from space latent heat gain of people and equipment, calculated by LOADS.

If F = CINF/CFM and DW = ΔW/RCFM, solving for WR,

$$WR = \frac{WCOIL + DW + (F * HUMRAT)}{1 + F}. \tag{IV.150}$$

The relationship between the mixed air humidity ratio (WM) and the fraction (PO) of outside ventilation air in the mixed air is,

$$WM = (PO * HUMRAT) + [(1.0 - PO) * WR]. \tag{IV.151}$$

By combining Eq. (IV.150) and Eq. (IV.151), and assuming that no moisture change occurs across the coil (that is, WM = WCOIL), a steady state expression for the supply air humidity ratio is obtained

$$WCOIL = WM = \frac{[(PO + F) * HUMRAT] + [(1.0 - PO) * DW]}{F + PO} \tag{IV.152}$$

$$WCOIL = WM = HUMRAT + \left[\frac{(1.0 - PO)}{F + PO} * DW\right].$$

The return air humidity ratio under these conditions (WM = WCOIL) is

$$WR = \frac{[(PO + F) * HUMRAT] + DW}{(PO + F)} \tag{IV.153}$$

$$WR = HUMRAT + \frac{DW}{PO + F}.$$

If the amount of outside ventilation air plus infiltration air is equal to zero, the right-hand side of Eq. (IV.153) is replaced with (HUMRAT + DW). If the calculated value for WR falls below the minimum level (WRMIN), calculated from the specified MIN-HUMIDITY at the return air temperature and outside atmospheric pressure, WMM is calculated as

$$WMM = [(1.0 + F) * WRMIN] - DW - (HUMRAT * F). \tag{IV.154}$$

This is the supply air humidity ratio required to maintain the specified return air humidity ratio. Thus, the resultant mixed air humidity ratio is

$$WM = (PO * HUMRAT) + [(1.0 - PO) * WRMIN], \tag{IV.155}$$

and the humidification heating energy is

$$QHUM = (WM - WMM) * CONS(2) * CFM. \tag{IV.156}$$

The total heating energy is calculated as the sum of the sensible and latent components

$$QH = \left\{CFM * D * [H(TM, WM) - H(TC,WM)]\right\} + QHUM, \tag{IV.157}$$

where

$D = \dfrac{60.0}{V(TM,WM,PATM)}$, the density of air at TM, WM, and PATM times 60 minutes/hour, and

H = the enthalphy of air at the conditions indicated.

G. If the system is in the cooling mode, calculate the coil surface temperature and its humidity ratio at saturation, the mixed air humidity ratio, the sensible cooling energy, and the dehumidification energy, if present.

If the coil entering air temperature (TM) is larger than the coil exit air temperature (TC), the air handler is in the net cooling mode. It is necessary to determine if the coil is dry or wet and whether or not humidity control will require further depression of the cooling coil exit air temperature. The contact between the cooling coil and the mixed air is characterized by the coil bypass factor (CBF). This value is assumed to be the product of the design bypass factor (COIL-BF) and two modifier functions to correct for off-design (off-rated) conditions

$$CBF = COIL\text{-}BF * CVAL(COIL\text{-}BF\text{-}FT,EWB,EDB) * CVAL(COIL\text{-}BF\text{-}FCFM,PLRCFM), \tag{IV.158}$$

where

COIL-BF-FT is a correction function to the coil bypass factor to adjust for off-rated entering wet-bulb and dry-bulb temperatures, COIL-BF-FCFM is a correction function to the coil bypass factor to adjust for off-rated air flow rate caused by part load operation,

EWB = the past hour's entering wet-bulb temperature,

EDB = TM for chilled water coils and DBT for direct expansion units, and

PLRCFM = CFM / SUPPLY-CFM.

To perform a moisture balance on the system, it is necessary to know the surface temperature of the cooling coil. This is calculated by using the bypass relationship,

$$TSURF = \frac{T - (CBF * TM)}{1.0 - CBF}, \qquad (IV.159)$$

where T is the average coil exit air temperature when the coil is extracting heat from the air stream. For chilled water coils, this is the average coil exit air temperature during the hour. For direct expansion units, the compressor may (1) be cycling on and off, (2) have a hot gas bypass, or (3) some combination of both. If the unit is either in an unloading mode or a hot gas bypass mode, to control the exit air temperature, the coil exit air temperature will be equal to that required for supply air temperature (TC). If the unit is cycling, the coil exit air temperature, during the time the compressor is on, is equal to the minimum available temperature (TDM)

TDM = TCMIN - DUCT-DELTA-T [however, if FAN-PLACEMENT = DRAW-THROUGH, TDM = TCMIN - DUCT-DELTA-T - SUPPLY-DELTA-T],

(IV.160)

If the previous hour's part load ratio (<PASTPLRC>) is less than the MIN-HGB-RATIO, it is assumed that the unit is cycling and the coil exit air temperature approaches the average for chilled water coils as the <PASTPLRC> approaches MIN-HGB-RATIO. Thus, the value from Eq. (IV.161) is added to that from Eq. (IV.160) to calculate the coil exit air temperature,

$$\left[\frac{\langle PASTPLRC\rangle}{MIN\text{-}HGB\text{-}RATIO}\right] * (TC - TDM). \qquad (IV.161)$$

The coil surface humidity ratio (WSURF) is calculated from the cooling coil surface temperature and the outside atmospheric pressure. Again, a moisture balance can be established for the dry coil, producing the same expression as in Eq. (IV.152). If no outside ventilation air or infiltration air is present, the right-hand side of this expression is replaced with (HUMRAT + DW). If the calculated value of the mixed air humidity ratio (WM) is less than the coil humidity ratio at saturation (WSURF), the coil is dry and it is only necessary to calculate the sensible cooling energy

$$QC = CFM * D * [H(TM,WM) - H(TC,WM)], \tag{IV.162}$$

where

$D = \frac{60.0}{V(TM,WM,PATM)}$ is the density of air at TM, WM, and PATM times 60 minutes/hour, and

H = the enthalpy of the air at the conditions indicated.

However, if the calculated mixed air humidity ratio is larger than WSURF, the coil is wet, that is, dehumidification occurs. The bypass model relates coil entering and exiting humidity ratios

$$WCOIL = (CBF * WM) + [(1.0 - CBF) * WSURF]. \tag{IV.163}$$

If Eqs. (IV.150), (IV.151), and (IV.163) are combined,

$$WR = \frac{(CBF * PO * HUMRAT) + [(1.0 - CBF) * WSURF] + DW + (F * HUMRAT)}{(1.0 + F) - [CBF * (1.0 - PO)]} . \tag{IV.164}$$

Then reapplying Eq. (IV.151) and Eq. (IV.163), the coil entering and exiting humidity ratios can be calculated. If the calculated return air humidity ratio from Eq. (IV.164) is larger than the maximum level (WRMAX), specified by MAX-HUMIDITY, the exit air temperature from the coil needs to be lowered to control humidity. The coil exit air temperature can only be lowered, however, if the current value of TC is larger than the minimum possible value (TDM). The coil surface conditions of temperature and humidity ratio at TDM are calculated as

$$TSURFM = \frac{TDM - (CBF * TM)}{1.0 - CBF} \text{ and} \tag{IV.165}$$

$$WSURFM = WFUNC(TSURFM,100.0,PATM). \tag{IV.166}$$

At the coil minimum supply temperature (TDM), the coil exit air humidity ratio (WCOLM) can be calculated

$$WCOLM = \frac{A + B}{1.0 + F - [CBF * (1.0 - PO)]}, \tag{IV.167}$$

where

A = (F + PO) * CBF * HUMRAT + (1.0 - PO) * CBF * DW, and
B = [(1.0 - CBF) * WSURFM].

The coil exit air humidity ratio required to maintain a return air humidity ratio of WRMAX is

$$WCOL = [(1.0 - F) * WRMAX] - DW - (F * HUMRAT), \tag{IV.168}$$

or WCOLM from Eq. (IV.167), whichever is larger.

Now, assume a linear interpolation between the initial coil exit air conditions (TC and WCOIL) and the minimum possible conditions (TDM and WCOLM). This will permit the calculation of the coil exit air temperature required to produce the desired exit air humidity ratio (WCOL) to control humidity. Thus, the temperature depression required (DTHUM) is

$$DTHUM = \frac{(WCOIL - WCOL)}{(WCOIL - WCOLM)} * (TC - TDM). \tag{IV.169}$$

Because depressing the coil exit air temperature, for humidity control, will also change the dry-bulb temperature of the air flowing into the spaces, it is necessary to (1) reduce the volume of supply air flow into the space (if variable volume flow is possible), (2) reheat the supply air, or (3) experience a combination of both to properly control the space sensible cooling load, without overcooling.

If the first approach is taken, the amount of supply air volume reduction is approximated by dividing the temperature reduction of the supply air (DTHUM) by the average supply air-to-space temperature gain (DTSUP).

DTSUP = (TR - DTP) - (TC + DUCT-DELTA-T) [however, if FAN-PLACEMENT = DRAW-THROUGH, DTSUP = (TR - DTP) - (TC + DUCT-DELTA-T + SUPPLY-DELTA-T)], (IV.170)

The new amount of cold air is CFMC

$$\text{CFMC} = \left[\frac{\text{DTSUP}}{\text{DTSUP + DTHUM}}\right] * \text{CFM}. \quad \text{(IV.171)}$$

If the second approach, reheating the supply air, is taken, the amount of air that needs to be reheated (CFMH) is calculated, taking into account the average MIN-CFM-RATIO

$$\text{CFMH} = (\text{MIN-CFM-RATIO} * \text{SUPPLY-CFM}) - \text{CFMC}. \quad \text{(IV.172)}$$

Next, the amount of dehumidification reheat (QDHUM) is calculated,

$$\text{QDHUM} = -\text{CONS}(1) * \text{DTSUP} * \text{CFMH} \quad \text{(IV.173)}$$

and the fan electrical energy consumption is adjusted by using a linear approximation over the range of this correction

$$\Delta\text{fan energy} \doteq \frac{\text{CFM - CFMH - CFMC}}{\text{CFM}} * (\text{SFKW + RFKW}), \quad \text{(IV.174)}$$

where SFKW and RFKW are the hourly electrical consumption rates of the supply air and return air fans, respectively.

Finally, the coil exit air temperature is decreased by DTHUM, and the supply and return air flows are then recalculated.

The total cooling coil load is calculated,

$$\text{QC} = \text{CFM} * \text{D} * [\text{H(TM,WM)} - \text{H(TC,WCOL)}], \quad \text{(IV.175)}$$

where

$\text{D} = \dfrac{60.0}{\text{V(TM,WM,PATM)}}$ is the density of air at TM, WM, and PATM times 60 minutes/hour, and

H = the enthalpy of air at the conditions indicated.

The moisture removal (in lbs. H_2O) across the cooling coil is

$$WW = (WM - WCOL) * CFM * D, \tag{IV.176}$$

and the latent cooling load (QCLAT) on the cooling coil is approximated, for reporting purposes, as

$$QCLAT = WW * 1061.0, \tag{IV.177}$$

where 1061.0 is the enthalpy of standard water vapor at 0°F in Btu/lb.

H. Calculate the cooling part load ratio.

Some central systems control the operation of the central cooling coil based upon temperature signals from the zone thermostats (COOL-CONTROL = WARMEST). Other central systems control the operation of the central cooling coil based upon the coil exit air temperature (COOL-CONTROL = CONSTANT, RESET, or SCHEDULED). In the latter case, the controller for the cooling coil has a throttling range. As the temperature of the air leaving the coil rises and falls within the controller's throttling range, the controller varies the operation of the coil, increasing or decreasing the output of the coil. The action of the controller must be simulated because it will have an effect on the coil surface conditions and thus also on moisture removal by the coil. Because this controller responds to the temperature of the air stream, the sensible part load ratio of the coil or unit will be calculated. This value will then be used the following hour to modify the coil exit air temperature as a function of controller set point, coil capacity, and controller throttling range (see DKTEMP algorithm description).

First, the program calculates the total and sensible cooling equipment capacities (QCT and QCS)

$$QCT = COOLING\text{-}CAPACITY * QCM1 \tag{IV.178}$$

where

QCM1 = CVAL(COOL-CAP-FT,EWB,EDB) [COOL-CAP-FT is a correction function to the total cooling capacity to adjust for off-rated entering wet-bulb and entering dry-bulb temperatures]

and

QCS = COOL-SH-CAP * QCM2 {however, for direct expansion units, QCS = (COOL-SH-CAP * QCM2) + [CONS(1) * CFM * (1.0 - CBF) * (TM - 80.0)]}

(IV.179)

<u>or</u>

QCS = QCT, whichever is smaller,

where

QCM2 = CVAL(COOL-SH-FT,EWB,EDB) [COOL-SH-FT is a correction function, similar to QCM1, but to the sensible portion of the total cooling capacity].

The equipment cooling part load ratio (PLRC) and the sensible part load ratio (<PASTPLRC>) are then calculated,

$$PLRC = \frac{QC}{QCT} \qquad (IV.180)$$

and

$$<PASTPLRC> = \frac{QC - QCLAT}{QCS} . \qquad (IV.181)$$

For direct expansion equipment, the electric power consumed by the heating element in the crankcase is calculated as CRANKCASE-HEAT * (1.0 - PLRC).

I. If the cooling is accomplished by direct expansion, calculate the energy consumption of the outside (condenser) fan and the compressor.

For direct expansion equipment, it is necessary to calculate the electrical energy input to the condenser and compressor units. The condensing unit may or may not have a fan. If the electrical input to a fan has not been included in the COOLING-EIR, the user has to specify it separately or ignore this energy input.

The outside (condenser) fan energy input (OFKW) is simply

$$OFKW = OUTSIDE\text{-}FAN\text{-}KW. \qquad (IV.182)$$

This energy is nonzero only if the outside air temperature is greater than or equal to the OUTSIDE-FAN-T, and cooling is scheduled to be on.

If the cooling load (QC) is not zero, the energy input to the compressor (QCKW) must be calculated. The design point (rated) EIR for the unit is adjusted for off-rated outdoor dry-bulb and entering wet-bulb temperatures, as well as for the part load operation of the compressor. These modifiers (EIRM1 and EIRM2) are calculated and multiplied by the design EIR to produce the operating EIR

EIRM1 = CVAL(COOL-EIR-FT,EWB,EDB) [COOL-EIR-FT is a correction function to the cooling electric input ratio to adjust for off-rated entering wet-bulb and entering dry-bulb temperatures].

(IV.183)

The part load operation of the compressor is the total load PLRC calculated, if the unit can unload to zero load. Otherwise, the unit will unload to a minimum point, then either cycle the compressor on and off or use a hot gas bypass to control compressor pressure difference. The COOL-EIR-FPLR performance function describes the part load characteristics above the MIN-UNLOAD-RATIO.

EIRM2 = CVAL(COOL-EIR-FPLR,PLRCC) (IV.184)

where [COOL-EIR-FPLR is a correction function to the cooling electric input ratio to adjust for the effect of part load operation] and PLRCC = PLRC or MIN-UNLOAD-RATIO, whichever is larger.

QCKW = QCT * EIR * 0.000293 (IV.185)

where

$.000293 \left(\text{or } \frac{1}{3413}\right)$ converts to Btu/hr to kilowatt-hr and

EIR = COOLING-EIR * EIRM1 * EIRM2.

If the part load ratio is between MIN-HGB-RATIO and MIN-UNLOAD-RATIO, the compressor is held at the same loading point by the hot gas bypass. It can be seen from Eq. (IV.184) and (IV.185) that, within this range, the energy input to handle the load is constant. If the load is less than MIN-HGB-RATIO, the equipment is assumed to be cycling, and that the compressor run time is linear with the load. Thus, the energy calculated in Eq. (IV.185) is multiplied by (PLRC / MIN-HGB-RATIO). If the OUTSIDE-FAN-MODE = INTERMITTENT, the outside (condenser) fan energy (OFKW) is multiplied by this same ratio. Thus, it can be seen that if the

MIN-UNLOAD-RATIO is equal to 1.0, COOL-EIR-FPLR has no effect, and below the MIN-UNLOAD-RATIO the energy input is linear down to zero load.

Finally, the amount of dehumidification reheat energy that can come from condenser heat recovery is calculated. This is the product of MAX-COND-RCVRY and the sum of the cooling load (QC) and the BTU equivalent of the compressor energy (QCKW).

3.1.3 Dual-Duct System Simulation for SYSTEM-TYPE = PMZS, MZS, or DDS (subroutines DOUBLE and DDSF)

These subroutines simulate the heat and moisture exchange in systems that use a dual-duct air-handling unit. This includes packaged multizone systems as well as built-up multizone and dual-duct systems, that is, SYSTEM-TYPE = PMZS, MZS, or DDS, respectively. The simulation of these dual-duct air-handling systems uses utility subroutines described elsewhere in this chapter, such as the supply air temperature calculation (subroutine DKTEMP), the zone air temperature calculation (subroutine TEMDEV), the outside ventilation air calculation (subroutine ECONO), and the fan energy consumption calculation (subroutine FANPWR). The main calculation sequence for these systems is divided into two parts: (1) the zone air-terminal calculation (subroutine DOUBLE) and (2) the air-handler calculation (subroutine DDSF).

Calculation Outline

I. Zone Air-Terminal Calculation (subroutine DOUBLE)

A. For VAV systems, calculate the maximum supply air CFM ratio allowed for the zones this hour.

B. Calculate the supply air temperatures (subroutine DKTEMP).

C. For each zone attached to this system,

1. calculate the maximum cooling and heating rates,
2. calculate the hourly zone temperature and the hourly cooling and heating rates (subroutine TEMDEV),
3. calculate the hot and cold duct supply air flow rates, and
4. sum the quantities needed for the air-handler calculation.

D. Calculate the return air flow rate and temperature.

E. Save all quantities that would be needed for a solar system simulation.

II. Dual-Duct Air-Handler Simulation (subroutine DDSF)

See Sec. IV.3.1.4.

Calculation Algorithms

I. Zone Air-Terminal Calculation (subroutine DOUBLE)

A. For VAV systems, calculate the maximum supply air CFM ratio allowed this hour.

If the system being simulated has air terminal boxes that have a variable air volume control capability, the amount of air that can be flowed into each zone can vary between some fixed minimum fraction (MIN-CFM-RATIO) of the design air flow rate and a maximum flow rate that depends upon the flow into the rest of the zones, but has an upper limit of the zone design flow rate. This maximum air flow rate may vary because although the volume control of the box may be wide open, the system fan may not be able to provide the design air flow rate because many of the other zone boxes are also wide open. If and when this occurs, it is because the fan SUPPLY-CFM times the MAX-FAN-RATIO is less than the sum of all the zone design flow rates.

Thus, if the average MIN-CFM-RATIO is less than 1.0 for this system (indicating a variable-air volume system), and either (1) the supply air fan was off the preceding hour or (2) the supply air fan CFM for the preceding hour (<PASTCFM>) was larger than SUPPLY-CFM, calculate

$$\text{CFMRAT} = \frac{\text{SUPPLY-CFM} * \text{MAX-FAN-RATIO} * (1.0 - \text{DUCT-AIR-LOSS})}{\displaystyle\sum_{nz=1}^{nzones} (\langle\text{CFMAX}\rangle_{nz} * \text{MULTIPLIER}_{nz})}, \tag{IV.186}$$

otherwise, CFMRAT is set equal to 1.0.

B. Calculate the supply air temperatures (subroutine DKTEMP).

DKTEMP is called to calculate the maximum and minimum supply air temperatures (THMAX and TCMIN), as well as the heating and cooling supply air temperatures, (TC) for the cold duct and (TH) for the hot duct.

C. For each zone attached to this system, calculate the equipment performance, as well as the zone conditions.

1. Calculate the maximum cooling and heating rates (<ERMAX> and <ERMIN>), as well as the heat extraction rate supplied when the zone temperature is within the thermostat deadband (ERMAXM). These values are first calculated by assuming that the zone remains at approximately a constant temperature that is equal to the value at the end of the previous hour. Subroutine TEMDEV will then correct these values of <ERMAX>, <ERMIN>, and ERMAXM for the change in the zone temperature during the current hour.

$$\langle\text{ERMAX}\rangle = \text{CONS}(1) * \langle\text{CFMAX}\rangle * \langle\text{CFMRAT}\rangle * (\langle\text{TNOW}\rangle - \text{TC}) \tag{IV.187}$$

where TC is the cold deck supply air temperature.

$$\langle\text{ERMIN}\rangle = \text{CONS}(1) * \text{CFMH} * (\langle\text{TNOW}\rangle - \text{TH}) \tag{IV.188}$$

where CFMH is <CFMAXH> or (<CFMAX> * CFMRAT), whichever is smaller, and TH is the hot deck supply air temperature.

$$\text{ERMAXM} = \text{CONS}(1) * \text{CFMIN} * (<\text{TNOW}> - \text{TC}) \tag{IV.189}$$

where CFMIN is (<CFMAX> * MIN-CFM-RATIO) or (<CFMAX> * CFMRAT), whichever is smaller.

Because reheat or recool are not used with these types of systems, it can be seen that the maximum and minimum zone supply air temperatures (THMAXZ and TCMINZ) are equal to the air handler hot and cold duct supply air temperatures (TH and TC).

2. Next, subroutine TEMDEV is called to calculate the current hour's zone temperature (<TNOW>) and the current hour's heating/cooling rate (<QNOW>). The average temperature during the hour (TAVE) is calculated as being halfway between <TNOW>, just calculated for the current hour, and <TPAST>, as calculated for the previous hour.

   TAVE is the temperature that will be used for all zone coil load calculations.

3. To calculate the hot and cold supply air flow rates to each zone (FH and FC), the program starts with the two relationships of the total air flow rate and the heating/cooling rate for the mixed air stream:

$$<\text{QNOW}> = \text{CONS}(1) * [\text{FC} * (\text{TAVE} - \text{TC}) + \text{FH} * (\text{TAVE} - \text{TH})] \tag{IV.190}$$

   and

$$\text{FH} + \text{FC} = \text{CFMIN}, \tag{IV.191}$$

   where CFMIN is the smaller of (<CFMAX> * MIN-CFM-RATIO) and (<CFMAX> * CFMRAT).

   If the net heating/cooling rate of the space is zero (<QNOW> = 0.0), Eqs. (IV.190) and (IV.191) can be combined to solve for FC,

$$\text{FC} = \text{CFMIN} * \left[\frac{\text{TAVE} - \text{TH}}{\text{TC} - \text{TH}}\right]. \tag{IV.192}$$

   Then, using Eq. (IV.191),

$$\text{FH} = \text{CFMIN} - \text{FC}. \tag{IV.193}$$

If the net heating/cooling rate is positive (<QNOW> is greater than zero), the cold air flow rate needed to handle the load is calculated as

$$FC = \frac{<\text{QNOW}>}{\text{CONS}(1) * (\text{TAVE} - \text{TC})} \cdot \qquad \text{(IV.194)}$$

If this quantity of FC is larger than the minimum air flow rate (CFMIN), it is not necessary to mix any hot air with the cold air to maintain the minimum air flow rate. If this value of FC is less than the minimum air flow rate, Eq. (IV.191) is substituted into Eq. (IV.190) and solving for FC

$$FC = \frac{<\text{QNOW}> - [\text{CONS}(1) * \text{CFMIN} * (\text{TAVE} - \text{TH})]}{\text{CONS}(1) * (\text{TH} - \text{TC})} . \qquad \text{(IV.195)}$$

Then, again using Eq. (IV.191), FH is recalculated.

If the net heating/cooling rate is less than zero, a similar procedure is used to calculate FH

$$FH = \frac{<\text{QNOW}>}{\text{CONS}(1) * (\text{TAVE} - \text{TH})} . \qquad \text{(IV.196)}$$

If this value of FH falls below the minimum (CFMIN), it is necessary to mix the two air streams.

$$FH = \frac{<\text{QNOW}> - [\text{CONS}(1) * \text{CFMIN} * (\text{TAVE} - \text{TC})]}{\text{CONS}(1) * (\text{TC} - \text{TH})} . \qquad \text{(IV.197)}$$

Then FC is calculated using Eq. (IV.191).

If the average zone temperature (TAVE) was within the thermostat deadband, the cold air supply flow rate (FC) and the hot air supply flow rate (FH) are set according to Eqs. (IV.192) and (IV.193).

4. To obtain system level performance data, several quantities need to be summed over all zones. These include total hot supply air flow rate,

$$\text{CFMH} = \sum_{nz=1}^{nzones} \text{FH}_{nz} * \text{MULTIPLIER}_{nz}, \qquad \text{(IV.198)}$$

cold supply air flow rate,

$$CFMC = \sum_{nz=1}^{nzones} FC_{nz} * MULTIPLIER_{nz}, \tag{IV.199}$$

exhaust air flow rate,

$$ECFM = \sum_{nz=1}^{nzones} EXHAUST\text{-}CFM_{nz} * MULTIPLIER_{nz}, \tag{IV.200}$$

heat of lights that are vented to the return air plenum,

$$QPSUM = \sum_{nz=1}^{nzones} \langle QP \rangle_{nz} * MULTIPLIER_{nz} \tag{IV.201}$$

where $\langle QP \rangle_{nz}$ is calculated by the LOADS program,

zone latent heat gain,

$$QLSUM = \sum_{nz=1}^{nzones} \langle QL \rangle_{nz} * RETR_{nz} * MULTIPLIER_{nz}, \tag{IV.202}$$

where $\langle QL \rangle_{nz}$ is calculated by the LOADS program and $RETR_{nz}$ is the ratio of exhaust air flow rate to supply air flow rate, and

and infiltration air flow rate,

$$CINF = \sum_{nz=1}^{nzones} \langle CFMINF \rangle_{nz} * RETR_{nz} * MULTIPLIER_{nz}. \tag{IV.203}$$

The electrical energy consumption by the zone is the sum of the exhaust fan energy consumption and the space electrical consumption calculated by the LOADS program (<ZKW>)

$$ZKW = EXHAUST\text{-}KW + <ZKW>. \qquad (IV.204)$$

The quantity (ZKW * MULTIPLIER) must be added to the total system electrical energy consumption (<SKW>). Also, the product of the exhaust fan electrical consumption and the zone multiplier is added to the total fan energy consumption (FANKW).

D. Calculate the return air flow rate and temperature.

The total supply air flow rate (CFM) is the sum of the hot and cold air flow rates (CFMH and CFMC). The return air flow rate (RCFM) is the supply air flow rate (CFM) minus the total exhaust air flow rate (ECFM). The return air temperature entering either the plenum or the ductwork is calculated as the weighted average of the zone temperatures,

$$TR = \frac{\sum_{nz=1}^{nzones} [TAVE_{nz} * (FH_{nz} + FC_{nz} - EXHAUST\text{-}CFM_{nz})] * MULTIPLIER_{nz}}{RCFM} . \qquad (IV.205)$$

E. Save all quantities that would be needed for a solar system simulation.

If the HEAT-SOURCE has been specified to be HOT-WATER/SOLAR, the program will save the main heating coil load (QH), the coil entering air temperature (TM), and supply air flow rate (CFM) for the solar system simulation. Similarly, if PREHEAT-SOURCE is specified to be HOT-WATER/SOLAR, the preheat coil load (QHP) and the outside ventilation air flow rate (PO * CFM) are saved for use by the solar system simulator.

3.1.4. Dual-Duct Air-Handler Simulation (subroutine DDSF)

Calculation Outline

A. Adjust the supply air CFM for duct air losses. Also, adjust the supply air temperatures (hot and cold) for duct temperature gains and losses. Calculate the minimum outside ventilation air fraction.

B. Calculate the supply and return fan energy consumption and the supply and return fan heat addition to the air stream (subroutine FANPWR).

C. Adjust the return air temperature for plenum effects.

D. Calculate the mixed air temperature (subroutine ECONO).

E. Calculate the preheat energy.

F. Calculate the heating and cooling coil energies (sensible and latent).

1. Assume a dry coil and calculate the mixed air humidity ratio.
2. Calculate the coil surface temperature and saturation humidity ratio.
3. If the mixed air humidity ratio is less than the coil surface humidity ratio at saturation, calculate the return air humidity ratio.
4. If the return air humidity ratio is less than the minimum specified, calculate the sensible heating, cooling, and humidification energy.
5. If the return air humidity ratio is larger than the minimum specified, calculate the sensible heating and cooling.
6. If the mixed air humidity ratio is larger than the coil surface humidity ratio at saturation, recalculate the mixed air, coil exit, and return air conditions (temperature and humidity ratio), assuming a wet coil.
7. If the return air humidity ratio is larger than the maximum specified, depress the coil exit air temperature to obtain humidity control.

G. Calculate the cooling part load ratio.

H. If cooling is accomplished by direct expansion,

1. calculate the outside fan energy consumption and
2. calculate the compressor energy consumption.

Calculation Algorithms

A. Adjust the supply air CFM for duct air losses. Also, adjust the supply air temperatures (hot and cold) for duct temperature gains and losses. Calculate the minimum outside ventilation air fraction.

The supply air flow rates and temperatures need to be adjusted for duct losses and gains. The air flow rates are divided by (1.0 - DUCT-AIR-LOSS) to adjust for air loss to the outside of the building. The cold supply air temperature is adjusted by subtracting DUCT-DELTA-T. The same quantity is added to the hot supply air temperature, unless the hot supply air temperature is less than the return air temperature. In this case, DUCT-DELTA-T is subtracted instead. These losses are meant to reflect energy that is lost from the building entirely, because they are not considered as contributing to the zone loads.

The minimum fraction (POM) of outside ventilation air in the total air supply, which corresponds to the minimum outside air damper position, is calculated by using either the specified MIN-OUTSIDE-AIR keyword value or the value referenced by MIN-AIR-SCH for the current hour. The latter overrides the former if it has been specified. This quantity is then compared to the total zone exhaust air flow rate (ECFM) and the larger of the two is used as POM.

B. Calculate the fan energy consumption and the fan heat addition to the air stream (subroutine FANPWR).

The subroutine FANPWR is called to calculate the electrical energy input to the supply air and return air fans (SFKW and RFKW). This subroutine will also calculate the ratio of the current hour's fan heat gain (to the air stream) to the design fan heat gain from the supply air and return air fans (DTS and DTR). These are then multiplied by the respective design values to produce the supply air and return air temperature rises (SUPPLY-DELTA-T and RETURN-DELTA-T).

C. Adjust the return air temperature for plenum effects.

The effect of heat from lights (that are vented to the return air plenum) on the return air stream and the interaction between the return air and plenum spaces needs to be calculated next. The temperature rise of the return air stream caused by heat from lights, specified in LOADS, is

$$DTP = \frac{QPSUM}{CONS(1) * RCFM} . \tag{IV.206}$$

The effect of plenum heat exchange for each zone is calculated by subroutine TEMDEV. The total effect of all plenums on the entire return air stream temperature is calculated by using the MULTIPLIER weighted average of all the plenums. Thus, the relationship of the temperature rise (TRA) and the total heat exchange between the plenums is expressed as

$$TRA = \frac{\sum_{np=1}^{nplenums} \langle QNOW\rangle_{np} * MULTIPLIER_{np}}{CONS(1) * RCFM} \tag{IV.207}$$

where <QNOW> is the heat exchanged with the plenum, as calculated by subroutine TEMDEV, and RCFM = CFM - ECFM.

D. Calculate the mixed air temperature (subroutine ECONO).

The mixed air controller set point temperature is determined by subtracting, from TC, the mixed air stream temperature rise caused by supply fan heat gain, in the case of a BLOW-THROUGH fan.

SUPPLY-DELTA-T * DTS.

The final return air temperature is found by adding the return air stream temperature rise, caused by return fan heat gain, to the exit weighted plenum air temperature. The return air stream temperature rise, caused by return fan heat gain, is calculated as

RETURN-DELTA-T * DTR.

The subroutine ECONO is then called to calculate the mixed air temperature (TM) and the fraction (PO) of outside ventilation air flow in the mixed air flow.

E. Calculate the preheat energy.

If the mixed air temperature is less than the PREHEAT-T, and heating is available, the preheat energy is calculated as

$$QHP = CONS(1) * CFM * (TM - PREHEAT\text{-}T), \tag{IV.208}$$

and the mixed air temperature is reset to the PREHEAT-T. The mixed air temperature (TM) is then increased by the temperature rise caused by supply fan heat gain.

F. Calculate the heating and cooling coil energies (sensible and latent).

In some types of dual-duct systems, it is possible for supply air to "wipe" across the heating coil before proceeding to the cold supply air duct and the cooling coil. This can happen because of (1) the heating coil placement, relative to the cooling coil placement, and/or (2) the closing of the hot supply air dampers thus creating turbulent air at the face of the coil. The user may have the program simulate this effect by using the HCOIL-WIPE-FCFM performance function. If this function has been defined, and heating is scheduled to be on for this hour, the fraction of cold supply air that first is heated to the hot supply temperature (PCH) is the value of the HCOIL-WIPE-FCFM at PC. The temperature of air entering the cooling coil is then,

$$TMC = (PCH * TH) + [(1.0 - PCH) * TM]. \tag{IV.209}$$

The first step in calculating the cooling and heating coil energy consumption is to see if the cooling coil is operating in the dry mode or the wet mode. Also, a check is made to see if humidification is necessary, to maintain a specified minimum humidity level. This is done by setting up a moisture balance for the system, equating gains and losses.

$$\begin{aligned}(CFM * WR) + (CINF * WR) &= (CFM * PH * WH) + (CFM * PC * WCOIL) \\ &\quad + (CINF * HUMRAT) + CFM + \Delta W \end{aligned} \tag{IV.210}$$

where WR = the return air humidity ratio,
WH = the hot air humidity ratio,
WCOIL = the cold air humidity ratio,
PH = that portion of CFM passing through the hot air duct,
PC = that portion of CFM passing through the cold air duct, and
ΔW = QLSUM/CONS(2), the space latent heat gain from people and equipment.

By definition, if F = CINF/CFM and DW = ΔW/RCFM, solving for WR,

$$WR = \frac{(PH * WH) + (PC * WCOIL) + DW + (F * HUMRAT)}{1.0 + F} . \tag{IV.211}$$

The relationship between the mixed (outside and return) air humidity ratio (WM) and the fraction (PO) of outside ventilation air in the mixed air is

$$WM = (PO * HUMRAT) + [(1.0 - PO) * WR]. \tag{IV.212}$$

If Eq. (IV.211) is combined with Eq. (IV.212), and assuming a dry coil (that is, WH = WCOIL = WM)

$$WM = \frac{[(F + PO) * HUMRAT] + [(1.0 - PO) * DW]}{F + PO} , \tag{IV.213}$$

$$WM = HUMRAT + \left[\frac{1.0 - PO}{F + PO} * DW\right].$$

The return air humidity ratio under these conditions (WH = WCOIL = WM) is

$$WR = \frac{[(F + PO) * HUMRAT] + DW}{F + PO} , \tag{IV.214}$$

$$WR = HUMRAT + \frac{DW}{F + PO} \cdot$$

If the amount of outside ventilation air plus infiltration air flow is zero, the right-hand side of Eqs. (IV.213) and (IV.214) can be replaced with (HUMRAT + DW).

Next, it is necessary to calculate the cooling coil surface conditions to see if the coil is operating in a wet mode. The contact between the cooling coil and the air is characterized by the coil bypass factor (CBF). This factor is assumed to be the product of the design value (COIL-BF) and two modifier functions to correct for off-design (off-rated) conditions.

$$CBF = COIL\text{-}BF * CVAL(COIL\text{-}BF\text{-}FT,EWB,EDB) * CVAL(COIL\text{-}BF\text{-}FCFM,PLRCFM) \tag{IV.215}$$

where

COIL-BF-FT is a correction function to the coil bypass factor to adjust for off-rated entering wet-bulb and entering dry-bulb temperatures,

COIL-BF-FCFM is a correction function to the coil bypass factor to adjust for off-rated air flow rate caused by part load operation,

EWB = the previous hour's entering wet-bulb temperature,

EDB = TMC for chilled water coils and DBT (outdoor dry-bulb temperature) for direct-expansion units, and

PLRCFM = (PC * CFM) / SUPPLY-CFM, the function of design flow through the cooling coil.

To perform a moisture balance on the system, it is necessary to know the surface temperature of the cooling coil. This is calculated by using the bypass relationship,

$$TSURF = \frac{T - (CBF * TM)}{1.0 - CBF}, \tag{IV.216}$$

where T is the average coil exit air temperature, when the coil is extracting heat from the air stream. For chilled water coils, this is the average cooling coil exit air temperature during the hour. For direct expansion units, the compressor may (1) be cycling on and off, (2) have a hot gas bypass, or (3) some combination of both. If the unit is either in an unloading mode or a hot gas bypass mode, to control the exit air temperature, the coil exit air temperature will be equal to that required for the supply air temperature (TC). If the unit is cycling, the coil exit air temperature, during the time the compressor is on, is equal to the minimum available temperature (TDM)

$$TDM = TCMIN - DUCT\text{-}DELTA\text{-}T. \tag{IV.217}$$

If the previous hour's part load ratio (<PASTPLRC>) is less than the MIN-HGB-RATIO, it is assumed that the unit is cycling and the coil exit air temperature approaches the average for chilled water coils as the part load ratio (<PASTPLRC>) approaches unity. Thus, the value from Eq. (IV.218) is added to that from Eq. (IV.217) to calculate the coil exit air temperature

$$\left[\frac{<PASTPLRC>}{MIN\text{-}HGB\text{-}RATIO}\right] * [TC - TDM_{Eq.\ IV.217}]. \tag{IV.218}$$

The coil surface humidity ratio at saturation (WSURF) is calculated from the cooling coil surface temperature and the outdoor atmospheric pressure. Again, a moisture balance can be established assuming a dry coil, producing the same expression as in Eq. (IV.213). If no outside ventilation air and infiltration air are present, the right-hand side of the expression is replaced with (HUMRAT + DW). If the calculated value of the mixed air humidity ratio (WM) is less than the coil surface humidity ratio at saturation (WSURF) and greater than the minimum value for the return air humidity ratio (WRMIN), defined by MIN-HUMIDITY at the current return air temperature, it is only necessary to calculate the sensible heating and cooling energy consumption.

$$QC = CFM * PC * D * [H(TMC,WM) - H(TH,WM)] \tag{IV.219}$$

$$QH = CFM * (PH + PCH * PC) * D * [H(TM,WM) - H(TH,WM)], \tag{IV.220}$$

where

PCH = the fraction of the cold supply air that wipes the hot coil,

$D = \frac{60.0}{V(TM,WM,PATM)}$, the density of air at TM, WM, and PATM times 60 minutes per hour, and

H = the enthalpy of air at the conditions indicated.

If the value calculated for WM is less than WRMIN, it is necessary to calculate the mixed air humidity ratio that would be required to meet the minimum humidity ratio (WMM), specified by the user with the keyword MIN-HUMIDITY,

$$WMM = [(1.0 + F) * WRMIN] - DW - (F * HUMRAT). \tag{IV.221}$$

The resultant mixed air humidity ratio is calculated from Eq. (IV.212), and the humidification energy is

$$QHUM = (WMM - WM) * CONS(2) * CFM. \tag{IV.222}$$

The sensible heating and cooling energies are calculated by using Eqs. (IV.219) and (IV.220) but substituting WMM for WM.

If the mixed air humidity ratio calculated by Eq. (IV.213) is larger than the coil surface humidity ratio at saturation (WSURF), the coil is wet, that is, dehumidification occurs. The bypass model relates coil entering and exiting air humidity ratios

$$WCOIL = (CBF * WM) + [(1.0 - CBF) * WSURF]. \tag{IV.223}$$

Combining Eqs. (IV.211), (IV.212), and (IV.223), produces Eq. (IV.224)

$$WR = \frac{A + B}{C}, \tag{IV.224}$$

where $A = (PH + PC * CBF) * PO * HUMRAT$,

$B = [PC * (1.0 - CBF) * WSURF] + DW + (F * HUMRAT)$, and

$C = 1.0 + F - [(PH + PC * CBF) * (1.0 - PO)]$.

Then reapplying Eqs. (IV.212) and (IV.223), the coil entering and exiting air humidity ratios can be calculated. If the calculated return air humidity ratio from Eq. (IV.224) is larger than the maximum level (WRMAX) specified by MAX-HUMIDITY, the exit air temperature from the cooling coil needs to be lowered to control humidity. The coil exit air temperature can only be lowered, however, if the current value of TC is larger than the minimum possible value (TDM), calculated from the minimum supply air temperature (TCMIN) and adjusted for duct heat gains.

The minimum possible coil surface temperature (TSURFM) and its corresponding saturation humidity ratio (WSURFM) are calculated at TDM by first applying Eq. (IV.216) and then the saturation humidity ratio at TSURFM is calculated. The coil exit air humidity ratio at TDM can then be calculated by again combining Eqs. (IV.211), (IV.212), and (IV.223), but solving for the coil exit air humidity ratio (WCOLM), that is, (WCOIL at TDM)

$$WCOLM = \frac{A + B}{C}, \qquad (IV.225)$$

where $A = CBF * [(F + PO) * HUMRAT + (1.0 - PO) * DW]$,

$B = [1.0 + F - PH * (1.0 - PO)] * (1.0 - CBF) * WSURFM$, and

$C = 1 + F - (1.0 - PO) * (PH + CBF * PC)$.

Now the program calculates the necessary coil exit condition for proper humidity control (WCOL), by substituting WRMAX into Eq. (IV.211) for WR and combining Eqs. (IV.211) and (IV.212) to get Eq. (IV.226)

$$WCOL = \frac{WRMAX * [1.0 + F - PH * (1.0 - PO)] - (PH * PO * F) * HUMRAT}{PC}. \qquad (IV.226)$$

If the value of WCOL from Eq. (IV.226) is less than than WCOLM, it is reset to WCOLM. Now, to calculate the required exit air temperature, a linear interpolation is used between the initial coil exit conditions (TC and WCOIL) and the minimum conditions (TDM and WCOLM). This will permit the program to calculate the coil exit air temperature required to produce the desired exit air humidity ratio (WCOL) to control humidity. Thus, the program calculates the temperature depression required (DTHUM)

$$DTHUM = \frac{(WCOIL - WCOL)}{(WCOIL - WCOLM)} * (TC - TDM). \qquad (IV.227)$$

Because depressing the coil exit air temperature, for humidity control, will also change the dry-bulb temperature of the air flowing into the spaces, it is necessary to (1) reduce the volume of supply air flow into the space (if variable volume flow is possible), (2) redistribute the supply air between the hot air and cold air ducts, or (3) experience some combination of both to properly control the space sensible cooling load, without overcooling. This readjustment can only be approximated because the details of each zone air terminal will most likely differ from the "average".

If the first approach is taken, the program will approximate the required cold air volume reduction by a reduction in the cold air supply temperature (DTHUM) divided by the average supply air-to-zone temperature gain. The new fraction of cold supply air is PCC

$$PCC = \left[1.0 - \frac{DTHUM}{(TR - DTP) - (TC + <DUCT-DELTA-T>)}\right]. \qquad (IV.228)$$

If variable-air-volume control to the zone is not possible, any decrease in the cold air flow rate must be accompanied by an identical increase in the hot air flow rate, to maintain a constant volume air flow. The new fraction of hot air (PHH) is estimated by taking into account the average MIN-CFM-RATIO.

$$\text{PHH} = \frac{[\text{MIN-CFM-RATIO} * \text{SUPPLY-CFM}] - [(\text{PH} + \text{PC}) * \text{CFM}]}{\text{CFM}}. \qquad \text{(IV.229)}$$

The old fractions of hot and cold air (PH and PC respectively) are reset to the new fractions, (PCC and PHH respectively). The coil exit air temperature is decreased by DTHUM. The sensible part of the extra dehumidification energy is estimated for the HOURLY-REPORTs as

$$\text{QDHUM} = -\text{CONS}(1) * \text{DTHUM} * \text{CFM} * \text{PCC}. \qquad \text{(IV.230)}$$

Next, it is necessary to adjust the fan energy consumption for any change in the total air flow rate. A linear approximation is used for this correction

$$\Delta\text{fan energy} = [1.0 - (\text{PH} + \text{PC})] * (\text{SFKW} + \text{RFKW}), \qquad \text{(IV.231)}$$

where SKFW and RFKW are the hourly electrical consumption rates of the supply air and return air fans, respectively.

The total heating and cooling coil energies are calculated as

$$\text{QH} = \text{CFM} * [\text{PH} + (\text{PCH} * \text{PC})] * \text{D} * [\text{H}(\text{TM},\text{WM}) - \text{H}(\text{TH},\text{WM})] \qquad \text{(IV.232)}$$

where

PCH = the fraction of the cold supply air that wipes the hot coil,

and

$$\text{QC} = \text{CFM} * \text{PC} * \text{D} * [\text{H}(\text{TM},\text{WM}) - \text{H}(\text{TC},\text{WCOIL})]$$

where

$\text{D} = \dfrac{60.0}{\text{V}(\text{TM},\text{WM},\text{PATM})}$ is the density of air at TM, WM, and PATM times 60 minutes/hour, and

H = the enthalpy of air at the conditions indicated.

The total water removal (WW in lbs. H_2O) and the resultant approximate latent cooling load, for reporting purposes, (QCLAT) are calculated as

$$WW = (WM - WCOIL) * CFM * D \tag{IV.233}$$

$$QCLAT = WW * 1061.0, \tag{IV.234}$$

where 1061.0 is the enthalpy of saturated water vapor at 0°F in Btu/lb.

G. Calculate the cooling part load ratio.

Some central systems control the operation of the central cooling coil based upon temperature signals from the zone thermostats (COOL-CONTROL = WARMEST). Other central systems control the operation of the central cooling coil based upon the coil exit air temperature (COOL-CONTROL = CONSTANT, RESET, or SCHEDULED). In the latter case, the controller for the cooling coil has a throttling range. As the temperature of the air leaving the coil rises and falls within the controller's throttling range, the controller varies the operation of the coil, increasing or decreasing the output of the coil. The action of the controller must be simulated because it will have an effect on the coil surface conditions and thus also on moisture removal by the coil. Because this controller responds to the temperature of the air stream, the sensible part load ratio of the coil or unit will be calculated. This value will then be used the following hour to modify the coil exit air temperature as a function of controller set point, coil capacity, and controller throttling range (see DKTEMP algorithm description).

First, the program calculates the total and sensible cooling equipment capacities (QCT and QCS)

$$QCT = COOLING\text{-}CAPACITY * QCM1 \tag{IV.235}$$

where

QCM1 = CVAL(COOL-CAP-FT, EWB, EDB) [COOL-CAP-FT is a correction function to the total cooling capacity to adjust for off-rated entering wet-bulb and entering dry-bulb temperatures]

and

QCS = COOL-SH-CAP * QCM2 {however, for direct expansion units, QCS = (COOL-SH-CAP * QCM2) + [CONS(1) * CFM * (1.0 - CBF) * (TM - 80.0)]}

(IV.236)

or

QCS = QCT, whichever is smaller,

where

QCM2 = CVAL(COOL-SH-FT,EWB,EDB) [COOL-SH-FT is a correction function similar to QCM1, but to the sensible portion of the total cooling load].

The equipment cooling part load ratio (PLRC) and the sensible part load ratio (<PASTPLRC>) are then calculated,

$$PLRC = \frac{QC}{QCT} \tag{IV.237}$$

and

$$\langle PASTPLRC \rangle = \frac{QC - QCLAT}{QCS} . \tag{IV.238}$$

For direct expansion equipment, the electric power consumed by the heating element in the crankcase is calculated as CRANKCASE-HEAT * (1.0 - PLRC).

H. If cooling is accomplished by direct expansion, calculate the outside (condenser) fan and compressor energy consumption.

For direct expansion equipment, it is necessary to calculate the electrical energy input to the condenser and compressor units. The condensing unit may or may not have a fan. If the electrical input to a fan has not been included in the COOLING-EIR, the user has to specify it separately or ignore this energy input.

The outside (condenser) fan energy input (OFKW) is simply

$$OFKW = OUTSIDE\text{-}FAN\text{-}KW. \tag{IV.239}$$

This energy is nonzero only if the outside air temperature is greater than or equal to the OUTSIDE-FAN-T, and cooling is scheduled to be on.

If the cooling load (QC) is not zero, the energy input to the compressor (QCKW) must be calculated. The design point (rated) EIR for the unit is adjusted for off-rated outdoor dry-bulb and entering wet-bulb temperatures, as well as for the part load operation of the compressor. These modifiers (EIRM1 and EIRM2) are calculated and multiplied by the design EIR to produce the operating EIR

EIRM1 = CVAL(COOL-EIR-FT, EWB, EDB) [COOL-EIR-FT is a correction function to the cooling electric input ratio to adjust for off-rated entering wet-bulb and entering dry-bulb temperatures].

(IV.240)

The part load operation of the compressor is the total PLRC calculated, if the unit can unload to zero load. Otherwise, the unit will unload to a minimum point, then either cycle the compressor on and off or use a hot gas bypass to control compressor pressure difference. The COOL-EIR-FPLR performance function describes the part load characteristics above the MIN-UNLOAD-RATIO.

EIRM2 = CVAL(COOL-EIR-FPLR,PLRCC) (IV.241)

where [COOL-EIR-FPLR is a correction function to the cooling electric input ratio to adjust for the effect of part load operation] and PLRCC = PLRC or MIN-UNLOAD-RATIO, whichever is larger.

QCKW = QCT * EIR * 0.000293 (IV.242)

where 0.000293 (or 1/3413) converts Btu/hr to kilowatt-hr and

EIR = COOLING-EIR * EIRM1 * EIRM2.

If the part load ratio is between MIN-HGB-RATIO and MIN-UNLOAD-RATIO, the compressor is held at the same loading point by the hot gas bypass. It can be seen from Eq. (IV.241) and (IV.242) that, within this range, the energy input to handle the load is constant. If the load is less than MIN-HGB-RATIO, the equipment is assumed to be cycling, and that the compressor run time is linear with the load. Thus, the energy calculated in Eq. (IV.242) is multiplied by (PLRC / MIN-HGB-RATIO). If the OUTSIDE-FAN-MODE = INTERMITTENT, the outside (condenser) fan energy (OFKW) is multiplied by this same ratio. Thus, it can be seen that if the MIN-UNLOAD-RATIO is equal to 1.0, COOL-EIR-FPLR has no effect, and below the MIN-UNLOAD-RATIO the energy input is linear down to zero load.

Finally, the amount of dehumidification reheat energy that can come from condenser heat recovery is calculated. This is the product of MAX-COND-RCVRY and the sum of the cooling load (QC) and the BTU equivalent of the compressor energy (QCKW).

3.1.5 Ceiling Induction System (subroutines SZCI and SDSF)

This subroutine, together with the single-duct air-handler subroutine (SDSF), will simulate the heat and moisture exchange in the system using a ceiling induction terminal unit, that is, SYSTEM-TYPE = SZCI. This subroutine uses other utility subroutines to calculate the supply temperature (subroutine DKTEMP) and the room air temperature (subroutine TEMDEV). The simulation proceeds in two major sections: (1) the zone terminal unit simulation (subroutine SZCI) and (2) the central air-handler simulation (subroutine SDSF).

Calculation Outline

I. Zone Air-Terminal Calculation (subroutine SZCI)

A. Calculate the maximum CFM ratio allowed for the zones this hour.

B. Calculate the supply air temperature (subroutine DKTEMP).

C. For each zone attached to this system,

   1. calculate the maximum cooling and heating rates,
   2. calculate the hourly zone temperature and the hourly cooling and heating rates (subroutine TEMDEV),
   3. calculate the primary and induced air flow rates and the reheat coil or baseboard input energy, and
   4. sum the quantities needed for the air-handler simulation.

D. Calculate the return air flow rate and temperature.

E. Save all quantities that would be needed for a solar system simulation.

II. Single-Duct Air-Handler Simulation (subroutine SDSF)

See Sec. IV.3.1.2.

Calculation Algorithms

I. Zone Air Terminal Calculation (subroutine SZCI)

A. Calculate the maximum supply air CFM ratio allowed for the zones this hour.

   The system being simulated has air terminal boxes that have an air volume control capability, the amount of air that can be passed into each zone can vary between a fixed minimum fraction of the design air flow rate (MIN-CFM-RATIO = .5) and a maximum flow rate that depends upon the flow into the rest of the zones, but has an upper limit of the zone design flow rate. This maximum flow rate may vary because although the volume control of the box may be wide open, the system fan may not be able to provide the design air flow rate because many of the other zone boxes are also wide open. If and when this occurs, it is because the fan SUPPLY-CFM times MAX-FAN-RATIO is less than the sum of all the zone design flow rates.

Thus, the average MIN-CFM-RATIO defaults to .5 (non-adjustable) for this system (indicating a variable-air volume system), but if either (1) the supply air fan was off the preceding hour or (2) the supply air fan CFM for the preceding hour (<PASTCFM>) was greater than SUPPLY-CFM, calculate

$$\text{CFMRAT} = \frac{\text{SUPPLY-CFM} * \text{MAX-FAN-RATIO} * (1.0 - \text{DUCT-AIR-LOSS})}{\sum_{nz=1}^{nzones} (\langle\text{CFMAX}\rangle_{nz} * \text{MULTIPLIER}_{nz})}, \tag{IV.243}$$

otherwise, CFMRAT is set equal to 1.0.

B. Calculate the supply air temperature (subroutine DKTEMP).

DKTEMP is called to calculate the maximum and minimum supply air temperatures (THMAX and TCMIN) for single-zone systems as well as the supply actual air temperature (TC) for multizone systems.

C. For each zone attached to this system, calculate the performance of the equipment in the zone, as well as the zone conditions.

The maximum heat extraction and addition rates are calculated, along with the minimum heat extraction rate (deadband extraction rate), by using the zone temperature at the end of the previous hour, the supply air temperature (TC), and the induced zone air temperature.

The induction air temperature is approximated by the previous hour's ending zone temperature (<TNOW>), modified for the current hour's heat gain (<QP>) from lights that are vented to the return air plenum (or zone).

$$\text{TL} = \langle\text{TNOW}\rangle + \frac{\langle\text{QP}\rangle}{\text{CONS}(1) * \langle\text{CFMAX}\rangle * \text{CFMRAT}} . \tag{IV.244}$$

The minimum temperature of air entering the zone (TCMINZ) is equal to the central air-handler supply temperature (TC). The maximum temperature of air entering the zone (THMAXZ) is the average temperature of the supply air from the air-handler and the induction zone air (because the maximum induction fraction is fixed at .5) plus the REHEAT-DELTA-T if heating is on. Thus, the maximum cooling and heating rates are given, respectively, as

$$\langle\text{ERMAX}\rangle = \text{CONS}(1) * \langle\text{CFMAX}\rangle * \text{CFMRAT} * (\langle\text{TNOW}\rangle - \text{TCMINZ}) \tag{IV.245}$$

and

$$\langle ERMIN \rangle = CONS(1) * \langle CFMAX \rangle * CFMRAT * (\langle TNOW \rangle - THMAXZ). \qquad (IV.246)$$

The minimum cooling rate, and the rate when the zone temperature is within the deadband of the thermostat, is calculated as

$$\langle ERMAXM \rangle = CONS(1) * \langle CFMAX \rangle * CFMRAT * \left[\langle TNOW \rangle - \left(\frac{TC + TL}{2.0}\right)\right]. \qquad (IV.247)$$

These cooling and heating rates are modified by the subroutine TEMDEV to account for the change in the zone temperature from last hour to the current hour. The average zone temperature (TAVE) is calculated as

$$TAVE = \frac{\langle TNOW \rangle + \langle TPAST \rangle}{2.0} .$$

This average temperature will be used for all zone coil load calculations.

TEMDEV, at this point, will also calculate the zone heat extraction/ addition rate for the current hour (<QNOW>).

If the average zone temperature is within the thermostat dead band, the induction box will be operating at its maximum induction fraction. Thus, the air flow rate from the central air-handler to the zone (CFMZ) is only half the design air flow rate times the maximum ratio allowed, that is, CFMZ = (<CFMAX> * CFMRAT)/2.0.

If the zone is in the heating mode (<QNOW> is less than or equal to zero), the induction box will be inducing maximum plenum air [CFMZ = (<CFMAX> * CFMRAT)/2.0]. Also, the reheat coil will be activated, if necessary, assuming it has been specified. The induction air temperature is recalculated as

$$TL = TAVE + \frac{\langle QP \rangle}{CONS(1) * (\langle CFMAX \rangle * CFMRAT - EXHAUST\text{-}CFM)} . \qquad (IV.248)$$

The reheat coil energy is composed of two parts: (1) the energy to produce zero net heat addition to the zone (ZQHR) and (2) the net zone load heat addition (<QNOW>).

$$ZQHR = CONS(1) * ZCFM * \left[\frac{TL + TC}{2.0} - TAVE\right], \qquad (IV.249)$$

where ZCFM = <CFMAX> * CFMRAT.

Then,

$$ZQH = ZQHR + \langle QNOW \rangle.$$

If the zone is in the net cooling mode (<QNOW> is greater than zero), as the zone temperature rises from the bottom to the top of the cooling THROTTLING-RANGE, the induction box opens towards full supply air flow from the central air-handler to handle the load. First, the subroutine calculates the heat extraction rate at maximum induction (bottom of the cooling THROTTLING-RANGE).

$$QRED = CONS(1) * ZCFM * \left[TAVE - \left(\frac{TL + TC}{2.0}\right)\right], \tag{IV.250}$$

where ZCFM and TL are calculated by using Eqs. (IV.248) and (IV.249) respectively. If the zone net heat extraction rate is less than this value, the subroutine must calculate the amount of reheat coil energy required to prevent overcooling of the zone

$$ZQHR = \langle QNOW \rangle - QRED, \tag{IV.251}$$

and the total reheat coil energy (QHZ) is set equal to this. If the zone net heat extraction rate is greater than the minimum (QRED), the induction box induces less plenum air to meet the zone temperature requirements. The net heat extraction rate can be related to the induction fraction

$$\langle QNOW \rangle = CONS(1) * ZCFM * [(1.0 - R) * (TAVE - TC) + R * (TAVE - TL)], \tag{IV.252}$$

where ZCFM and TL are as defined in Eqs. (IV.248) and (IV.249), and the induction fraction is R. Rearranging Eq. (IV.252) to solve for R gives

$$R = \frac{\dfrac{\langle QNOW \rangle}{CONS(1) * ZCFM} + (TC - TAVE)}{TC - TL}. \tag{IV.253}$$

Thus, the supply air flow rate from the central air-handler (CFMZ) is (1.0 - R) * ZCFM.

Because the baseboard heaters are assumed to be activated before the reheat coils, assuming both exist, the baseboard energy (QHBZ) is the greater (heating is negative) of either the total reheat (ZQH) or the BASEBOARD-RATING. The remainder of the reheat energy load is passed to the reheat coils through QHZ.

If the ZONE-HEAT-SOURCE has been specified as HOT-WATER/SOLAR, the subroutine will calculate and save the total zone heating coil load (QHZP), the air flow rate from the central air handler (CFMZP), and the average coil entering temperature (TZP) for use by the solar system simulation

$$QHZP = \sum_{nz=1}^{nzones} ZQH_{nz} * MULTIPLIER_{nz}, \tag{IV.254}$$

$$CFMZP = \sum_{nz=1}^{nzones} CFMZ_{nz} * MULTIPLIER_{nz}, \text{ and} \tag{IV.255}$$

$$TZP = \frac{\sum_{nz=1}^{nzones} \left\{ (TL_{nz} * R_{nz}) + [TC * (1.0 - R_{nz})] \right\} * CFMZ_{nz} * MULTIPLIER_{nz}}{CFMZP}. \tag{IV.256}$$

To obtain system level performance data, several quantities need to be summed over all the zones. These include exhaust air,

$$ECFM = \sum_{nz=1}^{nzones} EXHAUST\text{-}CFM_{nz} * MULTIPLIER_{nz}, \tag{IV.257}$$

exhaust fan energy consumption,

$$FANKW = \sum_{nz=1}^{nzones} EXHAUST\text{-}KW_{nz} * MULTIPLIER_{nz}, \tag{IV.258}$$

baseboard heater energy consumption,

$$QHB = \sum_{nz=1}^{nzones} QHBZ_{nz} * MULTIPLIER_{nz}, \qquad (IV.259)$$

total reheat coil energy consumption,

$$QHZ = \sum_{nz=1}^{nzones} ZQH_{nz} * MULTIPLIER_{nz}, \qquad (IV.260)$$

total electrical energy consumption,

$$\langle SKW\rangle = \sum_{nz=1}^{nzones} (\langle ZKW\rangle_{nz} + EXHAUST\text{-}KW_{nz}) * MULTIPLIER_{nz} , \qquad (IV.261)$$

infiltration air,

$$CINF = \sum_{nz=1}^{nzones} \langle CFMINF\rangle_{nz} * RETR_{nz} * MULTIPLIER_{nz} \qquad (IV.262)$$

$$\text{where } RETR_{nz} = \left(1.0 - \frac{EXHAUST\text{-}CFM_{nz}}{CFMZ_{nz}}\right) ,$$

and space latent heat gain from people and equipment,

$$QLSUM = \sum_{nz=1}^{nzones} \langle QL\rangle_{nz} * RETR_{nz} * MULTIPLIER_{nz} . \qquad (IV.263)$$

The total supply air flow rate is calculated as

$$CFM = \sum_{nz=1}^{nzones} \langle CFMZ \rangle_{nz} * MULTIPLIER_{nz}. \quad (IV.264)$$

The total heat of lights vented to the plenum (QPSUM) is set to zero, because it is already accounted for in the above calculations.

D. Calculate the return air flow rate and temperature.

The return air flow rate (RCFM) is the supply air flow rate (CFM) minus the total exhaust air flow rate (ECFM).

The return air temperature in the plenum or duct work is given by

$$TR = \frac{\sum_{nz=1}^{nzones} TL * (CFMZ_{nz} - ECFM_{nz}) * MULTIPLIER}{RCFM}. \quad (IV.265)$$

E. Save all quantitites that would be needed for a solar system simulation.

If the user specified SOLAR/HOT-WATER as an energy source for any of the coils (see SYSTEM instruction), information must be collected and passed to the PLANT program to aid in the simulation of solar system components.

The specification of ZONE-HEAT-SOURCE = SOLAR/HOT-WATER causes the program to calculate, at the SYSTEM level, the total zone coil load (QHZP), the total zone coil air flow rate (CFMZP), and the average zone coil entering temperature (TZP). These are calculated as

$$QHZP = \sum_{nz=1}^{nzones} \left(ZQH_{nz} * MULTIPLIER_{nz} \right), \quad (IV.266)$$

$$CFMZP = \sum_{nz=1}^{nzones} \left(CFMZ_{nz} * MULTIPLIER_{nz} \right), \text{ and} \quad (IV.267)$$

$$TZP = \frac{\sum_{nz=1}^{nzones} \left(TC * CFMZ_{nz} * MULTIPLIER_{nz} \right)}{CFMZP}. \quad (IV.268)$$

The specification of HEAT-SOURCE = SOLAR/HOT-WATER causes the program to calculate, at the PLANT level, the central heating coil load (QHMP), the total air flow rate (CFMP), and the average coil entering air temperature (TMP) for all systems in the PLANT-ASSIGNMENT instruction for which HEAT-SOURCE = SOLAR/HOT-WATER is specified. These quantities are calculated as

$$QHMP = \sum_{ns=1}^{nsystems} QH_{ns} , \tag{IV.269}$$

$$CFMP = \sum_{ns=1}^{nsystems} CFM_{ns} , \text{ and} \tag{IV.270}$$

$$TMP = \frac{\sum_{ns=1}^{nsystems} \left(TM_{ns} * CFM_{ns}\right)}{CFMP} . \tag{IV.271}$$

Similarly, for PREHEAT-SOURCE = SOLAR/HOT-WATER, the program calculates the total preheat load for all systems in the PLANT-ASSIGNMENT instruction,

$$QHPP = \sum_{ns=1}^{nsystems} QHP_{ns} \tag{IV.272}$$

and the total outside ventilation air flow rate for all systems in the PLANT-ASSIGNMENT instruction,

$$CFMPP = \sum_{ns=1}^{nsystems} PO_{ns} * CFM_{ns} , \tag{IV.273}$$

where PO_{ns} is the fraction of outside air flow in the total supply air flow for the system (CFM_{ns}).

II. Single-Duct Air-Handler Simulation (subroutine SDSF)

See Sec. IV.3.1.2.

3.1.6 Heating and Ventilating System (subroutine HVUNIT)

This subroutine simulates the performance of the constant air volume heating and ventilating system, that is, SYSTEM-TYPE = HVSYS. This simulation utilizes utility subroutines to calculate the room temperature and heat addition rate (subroutine TEMDEV), the outside ventilation air damper control (subroutine ECONO), and the fan electrical energy consumption (subroutine FANPWR). The basic configuration of this system is a central air handler with only a heating coil and zone air terminals with zone-controlled reheat coils.

Calculation Outline

A. Calculate the supply air temperature (subroutine DKTEMP).

B. For each zone attached to this system,

   1. calculate the maximum heating rate,
   2. calculate the hourly zone temperature and hourly heating rate (subroutine TEMDEV),
   3. calculate the reheat coil energy,
   4. sum the quantities needed for the air-handler calculation, and
   5. calculate the total supply air flow rate and the return air temperature.

C. Adjust the supply air CFM for duct losses. Calculate the minimum outside ventilation air fraction.

D. Calculate the fan energy consumption and the fan heat addition to the air stream (subroutine FANPWR).

E. Adjust the return air temperature for plenum effects.

F. Calculate the mixed air temperature (subroutine ECONO).

G. Calculate the mixed air humidity ratio, the return air humidity ratio, the sensible heating energy, and the humidification heating energy.

H. Save all quantities that would be needed for a solar system simulation.

Calculation Algorithms

A. Calculate the supply air temperature (subroutine DKTEMP).

   The subroutine DKTEMP calculates the heating supply air temperature (TH) for this hour from the air handler.

B. For each zone attached to this system, calculate the performance of the equipment in the zone, as well as the zone conditions.

1. The maximum supply air temperature entering each zone (THMAXZ) is the air handler supply temperature, adjusted for the reheat coil,

$$\text{THMAXZ} = \text{TH} + (\text{REHEAT-DELTA-T} * \text{HON}) \tag{IV.274}$$

or

MAX-SUPPLY-T, whichever is smaller.

HON is a heating flag. If heating is off, HON = 0 and if heating is on, HON = 1.

The maximum heat addition rate (<ERMIN>) can now be calculated by using this temperature

$$\langle\text{ERMIN}\rangle = \text{CONS}(1) * \langle\text{CFMAX}\rangle * (\langle\text{TNOW}\rangle - \text{THMAXZ}). \tag{IV.275}$$

The minimum supply air temperature entering each zone (TCMINZ) is the air temperature from the air handler (TH). The minimum heat addition rate (<ERMAX>) can be calculated, assuming air is passed into each zone at the air handler supply temperature

$$\langle\text{ERMAX}\rangle = \text{ERMAXM} = \text{CONS}(1) * \langle\text{CFMAX}\rangle * (\langle\text{TNOW}\rangle - \text{TH}). \tag{IV.276}$$

2. Subroutine TEMDEV next calculates the zone temperature at the end of the hour and the net heat addition rate during the hour (<QNOW>). The average zone temperature during the hour (TAVE) is calculated by using the value of the zone temperature from the end of the previous hour and the current hour,

$$\text{TAVE} = \frac{\langle\text{TNOW}\rangle + \langle\text{TPAST}\rangle}{2} .$$

This average zone temperature will be used in all subsequent zone coil load calculations.

3. If the zone temperature is within or below the heating throttling range, the reheat coil load is calculated,

$$\text{ZQH} = \langle\text{QNOW}\rangle + [\text{CONS}(1) * \langle\text{CFMAX}\rangle * (\text{TH} - \text{TAVE})]. \tag{IV.277}$$

The quantities ZQH and <QNOW> are negative, as are all heating quantities, but the quantity in the brackets is positive because (TH - TAVE) is positive.

4. To obtain system level performance data, several quantities need to be summed over all the zones. These include exhaust air cfm,

$$\text{ECFM} = \sum_{nz=1}^{nzones} \text{EXHAUST-CFM}_{nz} * \text{MULTIPLIER}_{nz}, \tag{IV.278}$$

exhaust fan energy consumption,

$$\text{FANKW} = \sum_{nz=1}^{nzones} \text{EXHAUST-KW}_{nz} * \text{MULTIPLIER}_{nz}, \tag{IV.279}$$

baseboard heater energy consumption,

$$\text{QHB} = \sum_{nz=1}^{nzones} \text{QHBZ}_{nz} * \text{MULTIPLIER}_{nz}, \tag{IV.280}$$

total reheat coil energy consumption,

$$\text{QHZ} = \sum_{nz=1}^{nzones} \text{ZQH}_{nz} * \text{MULTIPLIER}_{nz}, \tag{IV.281}$$

total electrical energy consumption,

$$<\text{SKW}> = \sum_{nz=1}^{nzones} (<\text{ZKW}>_{nz} + \text{EXHAUST-KW}_{nz}) * \text{MULTIPLIER}_{nz}\ , \tag{IV.282}$$

heat of lights that are vented to the return air plenum,

$$QPSUM = \sum_{nz=1}^{nzones} <QP>_{nz} * MULTIPLIER_{nz}, \qquad (IV.283)$$

infiltration air cfm,

$$CINF = \sum_{nz=1}^{nzones} <CFMINF>_{nz} * RETR_{nz} * MULTIPLIER_{nz} \qquad (IV.284)$$

$$\text{where } RETR_{nz} = \left(1.0 - \frac{EXHAUST\text{-}CFM_{nz}}{CFMZ_{nz}}\right),$$

and space latent heat gain from people and equipment,

$$QLSUM = \sum_{nz=1}^{nzones} <QL>_{nz} * RETR_{nz} * MULTIPLIER_{nz} . \qquad (IV.285)$$

5. Calculate the total supply air flow rate and the return air temperature.

$$CFM = \sum_{nz=1}^{nzones} <CFMAX>_{nz} * MULTIPLIER_{nz} \qquad (IV.286)$$

$$TR = \frac{\sum_{nz=1}^{nzones} (<CFMAX>_{nz} - EXHAUST\text{-}CFM_{nz}) * TAVE_{nz} * MULTIPLIER_{nz}}{CFM - ECFM} .$$

C. Adjust the supply air CFM for air duct losses. Calculate the minimum outside ventilation air fraction.

The supply air flow rate is adjusted for air losses to the outside of the building by dividing by (1.0 - DUCT-AIR-LOSS). The supply air temperature (TH) is adjusted for duct heat gains or losses. If TH is greater than the return air temperature, DUCT-DELTA-T is added to TH. If

TH is less than the return air temperature, DUCT-DELTA-T is subtracted from TH. The minimum ratio (POM) of outside ventilation air flow rate to the total supply air flow rate is calculated by using either the MIN-OUTSIDE-AIR value or the value referenced by the MIN-AIR-SCH for the current hour, if it has been specified. In addition, if the total zone exhaust air flow is greater than the value just described, it is used as the minimum outside air flow rate.

D. Calculate the fan energy consumption and the fan heat addition to the air stream (subroutine FANPWR).

The subroutine FANPWR is called to calculate the electric energy input to the supply air and return air fans (SFKW and RFKW). This subroutine will also determine the ratio of this hour's fan heat gain to the design fan heat gain for the supply air and return air fans (DTS and DTR).

E. Adjust the return air temperature for plenum effects.

The effect of heat from lights (that are vented to the plenum) on the return air stream and the interaction between the return air and plenum spaces needs to be calculated next. The temperature rise of the return air stream caused by heat from lights, specified in LOADS, is

$$DTP = \frac{QPSUM}{CONS(1) * RCFM} . \qquad (IV.287)$$

The effect of plenum heat exchange for each zone is calculated by TEMDEV. The total effect of all plenums on the entire return air stream temperature is calculated by using the MULTIPLIER weighted sum of all the plenums. Thus, the temperature rise (TRA) and the total heat exchange between the plenums are expressed as

$$TRA = \frac{\sum_{np=1}^{nplenums} \langle QNOW \rangle_{np} * MULTIPLIER_{np}}{CONS(1) * RCFM} \qquad (IV.288)$$

where <QNOW> is the heat exchanged with the plenum as calculated by TEMDEV.

F. Calculate the mixed air temperature (subroutine ECONO).

The mixed air controller set point temperature is determined by subtracting, from TH, the air stream temperature rise caused by supply fan heat gain,

SUPPLY-DELTA-T * DTS.

The final return air temperature is found by adding the return fan heat gain to the exit weighted plenum temperature. The return fan heat gain is calculated as

RETURN-DELTA-T * DTR.

The subroutine ECONO is then called to calculate the mixed air temperature (TM) and the fraction (PO) of outside ventilation air flow in the mixed air flow.

G. Calculate the mixed air humidity ratio, the return air humidity ratio, the sensible heating energy, and the humidification heating energy.

To see if humidification is necessary, a moisture balance on the entire system is performed

$$(CFM * WR) + (CINF * WR) = (CFM * WM) + (CINF * HUMRAT) + \Delta W \tag{IV.289}$$

where

WR = the return air humidity ratio,
CINF = the infiltration air flow rate,
HUMRAT = the outdoor humidity ratio,
WM = the mixed air humidity ratio, and

$\Delta W = \frac{QLSUM}{CONS(2)}$, the latent heat gain in the return air, from space latent heat gain of people and equipment, calculated by LOADS.

If F = CINF/CFM and DW = ΔW/RCFM, solving for WR,

$$WR = \frac{WM + DW + (F * HUMRAT)}{1 + F}. \tag{IV.290}$$

The relationship between the mixed air humidity ratio (WM) and the fraction (PO) of outside air in the mixed air is,

$$WM = (PO * HUMRAT) + [(1.0 - PO) * WR]. \tag{IV.291}$$

By combining Eq. (IV.290) and Eq. (IV.291), and assuming that no moisture change occurs across the coil (that is, WM = WCOIL), a steady state expression for the supply air humidity ratio is obtained

$$WM = \frac{[(PO + F) * HUMRAT] + [(1.0 - PO) * DW]}{F + PO}, \qquad (IV.292)$$

$$WM = HUMRAT + \left[\frac{(1.0 - PO)}{F + PO} * DW\right].$$

The return air humidity ratio under these conditions (WM = WCOIL) is

$$WR = \frac{[(PO + F) * HUMRAT] + DW}{(PO + F)}, \qquad (IV.293)$$

$$WR = HUMRAT + \frac{DW}{PO + F}.$$

If the amount of outside ventilation air plus infiltration is equal to zero, the right-hand side of Eq. (IV.293) is replaced with HUMRAT + DW. If the calculated value for WR falls below the minimum level (WRMIN), calculated from the specified MIN-HUMIDITY at the return air temperature and outside atmospheric pressure, WMM is calculated as

$$WMM = [(1.0 + F) * WRMIN] - DW - (HUMRAT * F). \qquad (IV.294)$$

This is the supply air humidity ratio required to maintain the specified return air condition. Thus, the resultant mixed air humidity ratio is

$$WM = (PO * HUMRAT) + [(1.0 - PO) * WRMIN], \qquad (IV.295)$$

and the humidification heating energy is

$$QHUM = (WM - WMM) * CONS(2) * CFM. \qquad (IV.296)$$

The total heating energy is calculated as the sum of the sensible and latent components

$$QH = \left\{CFM * D * [H(TM, WM) - H(TH,WM)]\right\} + QHUM, \qquad (IV.297)$$

where

H = the enthalpy of air at the conditions indicated and

$$D = \frac{60.0}{V(TM,WM,PATM)}$$, the density of air at TM, WM, and PATM, times 60 minutes/hour.

H. Save all quantities that would be needed for a solar system simulation.

If the user specified HOT-WATER/SOLAR as an energy source for any of the coils (see SYSTEM instruction), information must be collected and passed to the PLANT program to aid in the simulation of solar system components.

The specification of ZONE-HEAT-SOURCE = HOT-WATER/SOLAR causes the program to calculate, at the SYSTEM level, the total zone coil load (QHZP), the total zone coil air flow rate (CFMZP), and the average zone coil entering temperature (TZP). These are calculated as

$$QHZP = \sum_{nz=1}^{nzones} \left(ZQH_{nz} * MULTIPLIER_{nz}\right), \tag{IV.298}$$

$$CFMZP = \sum_{nz=1}^{nzones} \left(CFMZ_{nz} * MULTIPLIER_{nz}\right), \tag{IV.299}$$

$$TZP = \frac{\sum_{nz=1}^{nzones} \left(TC * CFMZ_{nz} * MULTIPLIER_{nz}\right)}{CFMZP} . \tag{IV.300}$$

The specification of HEAT-SOURCE = HOT-WATER/SOLAR causes the program to calculate, at the PLANT level, the central heating coil load (QHMP), the total air flow rate (CFMP), and the average coil entering temperature (TMP), for all systems in the PLANT-ASSIGNMENT instruction for which HEAT-SOURCE = HOT-WATER/SOLAR is specified. These quantities are calculated as

$$QHMP = \sum_{ns=1}^{nsystems} QH_{ns}, \tag{IV.301}$$

$$CFMP = \sum_{ns=1}^{nsystems} CFM_{ns}, \text{ and} \tag{IV.302}$$

$$TMP = \frac{\sum_{ns=1}^{nsystems} \left(TM_{ns} * CFM_{ns}\right)}{CFMP} . \tag{IV.303}$$

3.1.7 Induction Systems Simulation (subroutines INDUC and SDSF)

These subroutines simulate the heat and moisture exchanger in two- and four-pipe terminal induction systems. In DOE-2, these subroutines are used for SYSTEM-TYPE = TPIU and FPIU. These subroutines use other utility subroutines to calculate the hourly supply air temperature (subroutine DKTEMP) and the hourly room air temperature (subroutine TEMDEV). The simulation proceeds in two sections: (1) the zone terminal unit simulation (subroutine INDUC) and (2) the central air-handler simulation (subroutine SDSF).

Calculational Outline

I. Calculate the central air-handler supply air temperature (subroutine DKTEMP). For the two-pipe induction system, determine if heating or cooling is available to the zone terminals.

II. Zone Air Terminal Calculation (subroutine INDUC)

For each zone attached to this system,

A. calculate the maximum cooling and heating rates,
B. calculate the hourly zone temperature (subroutine TEMDEV),
C. calculate the heating or cooling energies for zone coils and baseboards (subroutine TEMDEV),
D. sum all quantities needed for the central air-handler simulation, and
E. calculate the return air flow rate and temperature.
F. Save all quantities that would be needed for a solar system simulation.

III. Single-Duct Air-Handler Simulation (subroutine SDSF).

See Sec. IV.3.1.2.

Calculation Algorithms

I. Calculate the central air-handler supply air temperature (subroutine DKTEMP)

For the two-pipe induction system, determine if heating and cooling are available to the zone terminals.

The subroutine DKTEMP calculates the supply air temperature from the central air handler (TC). If

(1) SYSTEM-TYPE = TPIU,
(2) the INDUC-MODE-SCH is calling for heating (that is, the referenced hourly value is less than zero), and
(3) COOL-CONTROL ≠ CONSTANT,

the value of the supply air temperature, calculated by subroutine DKTEMP, is reset to the larger of

(1) MIN-SUPPLY-T and
(2) TCMIN, as calculated by DKTEMP.

This is done so that when the zone terminal unit of a two-pipe induction system is switched from cooling to heating, the primary air becomes a cooling source. Otherwise, there would not be a source of cooling for those zones requiring cooling during the heating season, such as the interior zones of a building during the winter.

If the zone terminal units are in the heating mode (that is, the hourly value referenced by INDUC-MODE-SCH is less than zero), the subroutine will not allow air flow (primary air plus induced air) into the zone that is colder than that supplied by the central air handler. Similarly, when the zone terminal units are in the cooling mode, the subroutine will not allow air flow (primary air plus induced air) into the zones that is warmer than that supplied by the central air handler.

II. Zone Air Terminal Calculation (subroutine INDUC)

For each zone attached to the system, calculate the performance of the zone equipment, as well as the zone conditions.

Next, for each zone attached to this system, the subroutine simulates the terminal unit's interaction with the zone.

A. Calculate the maximum cooling and heating rates.

The next step is to calculate for each zone the maximum heat extraction and addition rates, as well as the extraction/addition rate when the zone temperature is within the dead band of the thermostat. The maximum and minimum zone supply air temperatures (THMAXZ and TCMINZ respectively) are calculated from the mixed air temperature (TC) from the air handler and the room air temperature <TNOW> from the induction process. Finally, the values of THMAXZ and TCMINZ are adjusted for heating or cooling from the zone coils. Again, a two-pipe system's zone coil mode is controlled by the INDUC-MODE-SCH.

The hourly temperature (TL) of the air entering the zone, from the terminal unit, is calculated from the supply air temperature (TC) leaving the central air handler and the induced air temperature (<TNOW>) in the zone.

$$TL = \frac{TC + (INDUCTION\text{-}RATIO * <TNOW>)}{1.0 + INDUCTION\text{-}RATIO} \qquad (IV.304)$$

This assumes that the zone coils in the terminal unit are not active. Thus, the maximum cooling and heating supply air temperatures (TCMINZ and THMAXZ) entering the zone are

$$TCMINZ = TL - \frac{<COOLCAPZ>}{CONS(1) * <CFMAX>} * CON \qquad (IV.305)$$

and

$$\mathrm{THMAXZ} = \mathrm{TL} - \frac{<\mathrm{HEATCAPZ}>}{\mathrm{CONS}(1) * <\mathrm{CFMAX}>} * \mathrm{HON}. \tag{IV.306}$$

<CFMAX> is the total zone air flow rate. <COOLCAPZ> is the cooling capacity of the zone cooling coil and <HEATCAPZ> is the heating capacity of the zone heating coil. CON and HON are, respectively, the cooling flag and the heating flag. A value of 1.0 indicates "on" and a value of 0. indicates "off". Both cooling and heating can be available in the zone at the same time, provided the COOLING-SCHEDULE and HEATING-SCHEDULE are specified to be on.

The maximum cooling and heating rates (ERMAX and ERMIN respectively) of the zone induction unit coil can now be calculated by Eq. (IV.307).

$$\begin{aligned} \mathrm{ERMAX} &= \mathrm{CONS}(1) * <\mathrm{CFMAX}> * (<\mathrm{TNOW}> - \mathrm{TCMINZ}) \\ \mathrm{ERMIN} &= \mathrm{CONS}(1) * <\mathrm{CFMAX}> * (<\mathrm{TNOW}> - \mathrm{THMAXZ}) \end{aligned} \tag{IV.307}$$

The dead band heat extraction rate can be calculated by assuming that the maximum induction temperature air is passed into the space untreated

$$\mathrm{ERMAXM} = \mathrm{CONS}(1) * <\mathrm{CFMAX}> * (<\mathrm{TNOW}> - \mathrm{TL}). \tag{IV.308}$$

B. Calculate the hourly zone temperature (subroutine TEMDEV).

Next, TEMDEV calculates the zone air temperature at the end of this hour and the total heat extraction/addition rate (<QNOW>) for the hour. The average temperature for the hour (TAVE) is calculated by using the temperature at the end of the past hour (<TPAST>) and this hour (<TNOW>)

$$\mathrm{TAVE} = \frac{<\mathrm{TPAST}> + <\mathrm{TNOW}>}{2} .$$

This average temperature will be used for all zone coil load calculations.

C. Calculate the heating and cooling energies for zone coils and baseboard heaters (subroutine TEMDEV).

If the average zone temperature is within the thermostat deadband, neither zone coil is active. If the average zone temperature is in either the heating or cooling throttling range, the load on the zone coils can be calculated as

$$Q = \langle QNOW \rangle - [CFMZ * (TAVE - TC)] \tag{IV.309}$$

where $CFMZ = \dfrac{\langle CFMAX \rangle}{1.0 + INDUCTION\text{-}RATIO}$.

If this quantity (Q) is negative, it is assigned to the zone heating coil as ZQH; if Q is positive, it is assigned to the zone cooling coil as ZQC.

D. Sum all quantities needed for the central air-handler simulation.

To obtain system level performance data, several quantities need to be summed over all the zones. These include exhaust air cfm,

$$ECFM = \sum_{nz=1}^{nzones} EXHAUST\text{-}CFM_{nz} * MULTIPLIER_{nz}, \tag{IV.310}$$

exhaust fan energy consumption,

$$FANKW = \sum_{nz=1}^{nzones} EXHAUST\text{-}KW_{nz} * MULTIPLIER_{nz}, \tag{IV.311}$$

baseboard heater energy consumption,

$$QHB = \sum_{nz=1}^{nzones} QHBZ_{nz} * MULTIPLIER_{nz}, \tag{IV.312}$$

total zone heating coil energy consumption,

$$QHZ = \sum_{nz=1}^{nzones} ZQH_{nz} * MULTIPLIER_{nz}, \tag{IV.313}$$

total zone cooling coil energy consumption,

$$QCZ = \sum_{nz=1}^{nzones} ZQC_{nz} * MULTIPLIER_{nz}, \qquad (IV.314)$$

total electrical energy consumption,

$$<SKW> = \sum_{nz=1}^{nzones} (<ZKW>_{nz} + EXHAUST\text{-}KW_{nz}) * MULTIPLIER_{nz} , \qquad (IV.315)$$

heat of lights that are vented to the return air plenum,

$$QPSUM = \sum_{nz=1}^{nzones} <QP>_{nz} * MULTIPLIER_{nz}, \qquad (IV.316)$$

infiltration air cfm,

$$CINF = \sum_{nz=1}^{nzones} <CFMINF>_{nz} * RETR_{nz} * MULTIPLIER_{nz} \qquad (IV.317)$$

$$\text{where } RETR_{nz} = \left(1.0 - \frac{EXHAUST\text{-}CFM_{nz}}{CFMZ_{nz}}\right) ,$$

space latent heat gain from people and equipment,

$$QLSUM = \sum_{nz=1}^{nzones} <QL>_{nz} * RETR_{nz} * MULTIPLIER_{nz}, \qquad (IV.318)$$

and total primary air flow rate,

$$CFM = \sum_{nz=1}^{nzones} CFMZ_{nz} * MULTIPLIER_{nz}. \quad (IV.319)$$

E. Calculate the return air flow rate and temperature.

The return air temperature (TR) in the plenum or return air system is calculated as

$$TR = \frac{\sum_{nz=1}^{nzones} TAVE_{nz} * (CFMZ_{nz} - EXHAUST\text{-}CFM_{nz}) * MULTIPLIER_{nz}}{RCFM} \quad (IV.320)$$

where RCFM = CFM - ECFM.

F. Save all quantitites that would be needed for a solar system simulation.

If the user specified SOLAR/HOT-WATER as an energy source for any of the coils (see SYSTEM instruction), information must be collected and passed to the PLANT program to aid in the simulation of solar system components.

The specification of ZONE-HEAT-SOURCE = SOLAR/HOT-WATER causes the program to calculate, at the SYSTEM level, the total zone coil load (QHZP), the total zone coil air flow rate (CFMZP), and the average zone coil entering temperature (TZP). These are calculated as

$$QHZP = \sum_{nz=1}^{nzones} \left(ZQH_{nz} * MULTIPLIER_{nz}\right), \quad (IV.321)$$

$$CFMZP = \sum_{nz=1}^{nzones} \left(CFMZ_{nz} * MULTIPLIER_{nz}\right), \text{ and} \quad (IV.322)$$

$$TZP = \frac{\sum_{nz=1}^{nzones} \left(TL * CFMZ_{nz} * MULTIPLIER_{nz}\right)}{CFMZP}. \quad (IV.323)$$

The specification of HEAT-SOURCE = SOLAR/HOT-WATER causes the program to calculate, at the PLANT level, the central heating coil load (QHMP), the total air flow rate (CFMP), and the average coil entering air temperature (TMP) for all systems in the PLANT-ASSIGNMENT instruction for which HEAT-SOURCE = SOLAR/HOT-WATER is specified. These quantities are calculated as

$$QHMP = \sum_{ns=1}^{nsystems} QH_{ns} , \tag{IV.324}$$

$$CFMP = \sum_{ns=1}^{nsystems} CFM_{ns} , \text{ and} \tag{IV.325}$$

$$TMP = \frac{\sum_{ns=1}^{nsystems} \left(TM_{ns} * CFM_{ns} \right)}{CFMP} . \tag{IV.326}$$

Similarly, for PREHEAT-SOURCE = SOLAR/HOT-WATER, the program calculates the total preheat load for all systems in the PLANT-ASSIGNMENT instruction,

$$QHPP = \sum_{ns=1}^{nsystems} QHP_{ns} \tag{IV.327}$$

and the total outside ventilation air flow rate for all systems in the PLANT-ASSIGNMENT instruction,

$$CFMPP = \sum_{ns=1}^{nsystems} PO_{ns} * CFM_{ns} , \tag{IV.328}$$

where PO_{ns} is the fraction of outside ventilation air flow in the total supply air flow for the system (CFM_{ns}).

III. Simulate the central air handler (subroutine SDSF)

See Sec. IV.3.1.2.

3.1.8 Residential System (subroutine RESYS)

This subroutine simulates the heat and moisture exchange in common residential heating and air-conditioning systems (SYSTEM-TYPE = RESYS). The system simulated includes central forced air heating from a hot water coil, a heat pump, or a furnace fueled by gas, oil, or electricity. The zone(s) may contain zone-controlled baseboard heaters, which use either electricity or hot water as a heat source. If a hot water coil is simulated, the load is passed to the PLANT program to permit solar-assisted heating. A central forced air direct expansion cooling system is also simulated.

Calculation Outline

I. Simulate the equipment action for each zone attached to this SYSTEM

A. Calculate the maximum cooling and heating rates. For the control zone, calculate the central unit capacity and the supply air temperature.

B. For each zone attached to this system,

1. calculate the correction term for interzone heat transfer,
2. correct for the incorrect use of LIGHT-TO-SPACE in LOADS and simulate the outdoor-reset baseboard heaters,
3. correct the maximum and minimum cooling and heating rates for zone temperature change during the hour,
4. calculate the hourly zone temperature and the hourly cooling and heating rates

    a. within the deadband, during heating or cooling, and
    b. during ventilating,

5. simulate the thermostatically-controlled baseboards,
6. update the zone temperature and heat addition/extraction history, and
7. perform calculations for unconditioned zones.

C. For the control zone, calculate the fan part load ratio.

D. Sum the necessary information for the simulation of the central HVAC unit.

II. Simulate the central HVAC unit performance

A. If the HVAC unit has a dual speed compressor, determine if it is running at high speed or low speed.

B. Simulate the central HVAC unit in,

1. the cooling mode and
2. the heating mode.

C. Save all quantities that would be needed for a solar equipment simulation.

Calculation Algorithms

I. Simulate the equipment action for each zone attached to this system

In this system, the central heating and cooling unit is assumed to be controlled by a thermostat placed in the control zone (first zone specified for the keyword ZONE-NAMES in the SYSTEM instruction). Therefore, as the program simulates the actions in all the zones attached to this system, the first zone's thermostat action will control the volume of air supplied to the other conditioned zones (subzones). The thermostats in the subzones are only used to control thermostatic baseboard heaters.

A. For the control zone, calculate the central unit capacity and the supply air temperature. Once the supply air temperature and flow rate are known, it is possible to calculate the maximum cooling and heating rates for all zones.

If this zone is the control zone, it is first necessary to calculate the HVAC unit capacity so that the supply air temperature can then be calculated (subroutine DKTEMP). Initially, the dry-bulb temperature of the coil entering air (TM) is estimated to be the zone temperature at the end of the previous hour <TNOW>, adjusted for fan heat gain

TM = <TNOW> + SUPPLY-DELTA-T. (IV.329)

The total and sensible cooling capacities (QCT and QCS respectively) are calculated by using the entering dry- and wet-bulb temperatures (wet-bulb from the previous hour), as well as outdoor dry-bulb temperature

QCT = COOLING-CAPACITY * CVAL(COOL-CAP-FT,EWB,T) (IV.330)

and

QCS = Smaller of [COOL-SH-CAP * CVAL(COOL-SH-FT,EWB,T)
* (1.0 - COIL-BF) * (TM - 80.0)], (IV.331)

and QCT,

where

COOL-CAP-FT is a correction function to the total cooling capacity to adjust for off-rated entering wet-bulb (EWB) and entering dry-bulb (T) temperatures,

COOL-SH-FT is a correction function to the sensible cooling capacity to adjust for off-rated wet-bulb (EWB) and entering dry-bulb (T) temperatures,

EWB = the larger of <PASTWBZ> and 60.0, and

T = the larger of DBT and COOL-FT-MIN.

COOL-FT-MIN is the minimum outdoor dry-bulb temperature for the equipment performance curves referenced by COOL-CAP-FT, COOL-EIR-FT, and COOL-SH-FT. This is the minimum extrapolation point. Below this point the accuracy of the three curves is degraded.

Thus, the minimum zone supply air temperature (TCMINZ) can be calculated, along with the maximum heat extraction rate (<ERMAX>)

$$TCMIN = TM - \frac{QCS * CON}{CONS(1) * <CFMAX>} \text{ or MIN-SUPPLY-T,} \tag{IV.332}$$

whichever is larger. CON is a cooling flag; if CON = 1, the cooling is on and if CON = 0, the cooling is off.

$$<ERMAX> = CONS(1) * <CFMAX> * (<TNOW> - TCMIN) \tag{IV.333}$$

If the zone temperature is within the deadband of the thermostat, the heat extraction rate is zero; that is,

$$ERMAXM = 0.0. \tag{IV.334}$$

This is because this system cycles on and off, based upon the load in the control zone.

In a similar manner, the heating capacity (QHT), the maximum supply air temperature (THMAX), and the maximum heat addition rate (<ERMIN>) may be calculated. If the HEAT-SOURCE is <u>not</u> HEAT-PUMP, the capacity is the constant unit heating capacity (HEATING-CAPACITY). Otherwise, it is necessary to calculate the capacity of the air-to-air heat pump (QHPT) and the capacity of the electric resistance heater (QE), if specified.

$$\begin{aligned} QHT &= \text{HEATING-CAPACITY, if HEAT-SOURCE} \neq \text{HEAT-PUMP but} \\ QHT &= QHPT + QE, \text{ if HEAT-SOURCE = HEAT-PUMP} \end{aligned} \tag{IV.335}$$

where

$$\begin{aligned} QHPT &= \text{HEATING-CAPACITY * CVAL(HEAT-CAP-FT,DBT,TM) or 0.0,} \\ &\quad \text{if DBT} < \text{MIN-HP-T, and} \\ QE &= \text{ELEC-HEAT-CAP or 0.0, if DBT} > \text{MAX-ELEC-T,} \end{aligned}$$

$$\mathrm{THMAX} = \mathrm{TM} - \frac{\mathrm{QHT} * \mathrm{HON}}{\mathrm{CONS}(1) * <\mathrm{CFMAX}>}, \text{ and} \tag{IV.336}$$

$$<\mathrm{ERMIN}> = \mathrm{CONS}(1) * <\mathrm{CFMAX}> * (<\mathrm{TNOW}> - \mathrm{THMAX}). \tag{IV.337}$$

HEAT-CAP-FT is a correction function to the total heat pump heating capacity to adjust for off-rated outdoor dry-bulb temperature (DBT) and mixed air dry-bulb temperature (TM).

MIN-HP-T is the outdoor dry-bulb temperature below which the heat pump is turned off. MAX-ELEC-T is the maximum outdoor dry-bulb temperature above which the electric resistance heater is turned off. HON is the heating flag; if HON = 1, the heating is on and if HON = 0, the heating is off.

If this is a subzone (a conditioned zone but not the first zone specified), the minimum and maximum supply air temperatures are the same as for the control zone, from Eqs. (IV.332) and (IV.336), but the maximum cooling and heating rates are calculated by assuming that these subzones receive the same temperature air, for the same fraction of the hour, as the control zone

$$<\mathrm{ERMAX}> = \mathrm{CONS}(1) * <\mathrm{CFMAX}> * (<\mathrm{TNOW}> - \mathrm{TCMIN}) * \mathrm{PLRC} \tag{IV.338}$$

$$<\mathrm{ERMIN}> = \mathrm{CONS}(1) * <\mathrm{CFMAX}> * (<\mathrm{TNOW}> - \mathrm{THMAX}) * \mathrm{PLRH} \tag{IV.339}$$

where PLRC and PLRH are the supply air fan cooling and heating part load ratios (that is, the fraction of the hour that the supply air fan runs to deliver cold or hot air). These part load ratios are calculated for the control zone.

The deadband heat extraction/addition rate (ERMAXM) for subzones is set equal to the sum of <ERMAX> and <ERMIN> (one or the other of which is always zero).

B. For each zone attached to this system, calculate the heat extraction/addition rate to the zone, as well as the zone temperature.

1. Calculate the correction term for interzone heat transfer.

The LOADS program calculates the thermal conductance of energy between any two contiguous zones by using a U * A * (T_1-T_2) relationship. The U * A term is the sum (for all interior walls between this zone and its contiguous zones) of the products of the U-value specified for the wall and the area of the wall. The $(T_1 - T_2)$ term is calculated by using the LOADS calculation temperatures of the two zones. Thus, the quantity [U * A * (T_1-T_2)] is a constant as far as the LOADS program is concerned. SYSTEMS, however, cannot treat this quantity as a constant because the air temperatures within the zones of the building are allowed to change with time. Thus, the SYSTEMS program must calculate the correction to this term [$(T_1 - T_2)$] that will compensate for the zones not being at their constant LOADS calculation temperatures.

Equation (IV.340) presents the transfer function relationship between the room air temperature plus its history and the heat extraction/addition rate plus its history

$$\left\{\begin{array}{r} (HENOW - <QS>) + \\ <P1> * (<QNOW> - <QSPAST>) + \\ <P2> * (<QPAST> - <QSPAST2>) \end{array}\right\} = \left\{\begin{array}{l} G0 * (<TLOADS> - TRY) + \\ G1 * (<TLOADS> - <TNOW>) + \\ G2 * (<TLOADS> - <TPAST>) + \\ G3 * (<TLOADS> - <TPAST2>) \end{array}\right\} \qquad (IV.340)$$

where

<TLOADS>	is the temperature of the zone, as specified by the user in LOADS,
<P1>, <P2>	are room air weighting factors from LOADS,
G0, G1, G2, G3	are room air weighting factors (defined later),
<QS>, <QSPAST>, <QSPAST2>	are constant-temperature sensible heat extraction/addition loads, calculated by LOADS, for the current and past two hours,
HENOW, <QNOW>, <QPAST>	are the current and past two hours' history of zone heat extraction/addition rates, calculated by SYSTEMS, and
TRY <TNOW> <TPAST> <TPAST2>	are the current and past three hours' history of zone temperature.

By rearranging terms,

$$HENOW = F - (G0 * TRY) \qquad (IV.341)$$

where

$$\begin{aligned} F = {} & (<TLOADS> * SIGMAG) + <QNOW> + [<P1> * (<QSPAST> - <QNOW>)] \\ & + [<P2> * (<QSPAST2> - <QPAST>)] - (G1 * <TNOW>) \\ & - (G2 * <TPAST>) - (G3 * <TPAST2>), \end{aligned}$$

$$SIGMAG = G0 + G1 + G2 + G3.$$

If, additionally, it is assumed that a linear relationship exists between the thermostat action within a control band and the zone temperature,

$$HENOW = W + (S * TRY) \tag{IV.342}$$

where, on a plot of zone temperature vs. heat extraction/addition rate (see Sec. IV.1.1), S is the slope of the line and W is the intercept of the line.

Combining Eqs. (IV.341) and (IV.342) and solving first for HENOW,

$$HENOW = \frac{(G0 * W) + (F * S)}{S + G0} . \tag{IV.343}$$

This is then substituted back into Eq. (IV.341) and solving for TRY produces

$$TRY = \frac{F - HENOW}{G0} . \tag{IV.344}$$

These are the basic relationships, which are outlined in the overview and weighting factor sections, that are used to obtain the zone air temperature and the heat extraction/addition rate, by knowing the equipment capacity and the thermostat action characteristics.

Terms G0, G1, G2, and G3 are defined as

G0 = (<G0> * <AREA>) + [<CONDUCHR> + (CONS(1) * <CFMINF>)]
G1 = (<G1> * <AREA>) + {<P1> * [<CONDUCHRPAST> + (CONS(1) * <VIPAST>)]}
G2 = (<G2> * <AREA>) + {<P2> * [<CONDUCHRPAST2> + (CONS(1) * <VIPAST>)]}
G3 = (<G3> * <AREA>)

where <G0>, <G1>, <G2>, and <G3> are the "normalized" room air temperature weighting factors from LOADS, <AREA> is the zone area, and <CONDUCHR>, <CONDUCHRPAST>, and <CONDUCHRPAST2> are the sum of exterior wall and interior wall thermal conductances for the present and past two hours.

Now, let the thermal conductance terms in the G0, G1, and G2 terms be composed of both exterior and interior components

$$\langle CONDUCHR \rangle = k_{ext} + \sum_{n=1}^{\langle nattch \rangle} k_n \tag{IV.345}$$

where k_{ext} is the external surfaces summed thermal conductance and k_n is the thermal conductance of the $\underline{n}$th internal surface separating one zone from the other attached zones.

Using similar expressions from <CONDUCHRPAST> and <CONDUCHRPAST2>, and by knowing that the sensible load from LOADS already contains the correction for different constant-LOADS calculation temperatures, a new term for the right-hand side of Eq. (IV.341) becomes

$$HENOW = F + \left[\sum_{i=0}^{2} P_i \sum_{j=1}^{\langle nattch \rangle} (T_{j,t-i} - T_{j,L}) \right] - (GO * TRY) \tag{IV.346}$$

where

P_0, P_1, and P_2 are 1.0, <P1>, and <P2>, respectively,

$T_{j,t-i}$ is the temperature of the jth attached space t-i hours past; and

$T_{j,L}$ is the constant-LOADS calculation temperature of the jth attached space.

Using Eq. (IV.346) to get an analogous expression for Eqs. (IV.343) and (IV.344) would require solving all zones simultaneously. To avoid this, substitute $T_{j,t-i-1}$ for $T_{j,t-i}$ in Eq. (IV.346). This simplification assumes that the change in slope of the temperature of all zones is not changing greatly from hour to hour. Thus, the correction for the internal heat transfer is

$$CORINT = X + (\langle P1 \rangle * Y) + (\langle PZ \rangle * Z) \tag{IV.347}$$

where

$$X = \sum_{NATTSP=1}^{\langle NATTCH \rangle} AA(I1+1) * [TEMPS(1,NATTSP,NP) - TEMPSL(NATTSP)],$$

$$Y = \sum_{NATTSP=1}^{<NATTCH>} AA(I1+1) * [TEMPS(2,NATTSP,NP) - TEMPSL(NATTSP)],$$

and

$$Z = \sum_{NATTSP=1}^{<NATTCH>} AA(I1+1) * [TEMPS(3,NATTSP,NP) - TEMPSL(NATTSP)],$$

AA(I1+1) = the sum of U*A for all interior walls separating the space being simulated and space j,

TEMPS(i,NATTSP,NP) = the temperature, during the ith past hour, of the NATTSPth attached space in NPth PLANT-ASSIGNMENT, and

TEMPSL(NATTSP) = the LOADS-calculated temperature of the NATTSPth attached space.

The value of CORINT is added to that of F, producing a new value for F.

2. Correct for the incorrect use of LIGHT-TO-SPACE, in LOADS, and simulate the outdoor-reset baseboard heaters.

This SYSTEM-TYPE cannot have any zones that function like plenums (that is, ZONE-TYPE = PLENUM). Also, this SYSTEM-TYPE permits the simulation of outdoor-reset baseboard heaters. Both of these traits require modification to Eq. (IV.340).

For SYSTEM-TYPEs that do not allow plenums, the subroutine must override a user specification of LIGHT-TO-SPACE not equal to 100.0. This is done by adding the plenum heat gain from this space (<QPNOW> or <QP> as calculated by LOADS and passed to SYSTEMS) back into the sensible load (<QS>) in Eq. (IV.340). It is also necessary to save the <QP> history (<QPAST> and <QPAST2>) for the past two hours, to modify <QSPAST> and <QSPAST2> in Eq. (IV.341).

If the system has outdoor-reset baseboard heaters, the subroutine calculates the output from the baseboards of this zone as

$$QHBZ = BON * <BASEBOARD\text{-}RATING>$$

where

$$BON = SH + \left[\frac{SL - SH}{RH - RL}\right] * (DBT - RL),$$

SH = SUPPLY-HI
SL = SUPPLY-LO
RH = OUTSIDE-HI
RL = OUTSIDE-HI

as specified by the user, with the keyword BASEBOARD-SCH and the commands BASEBOARD-SCH and the commands DAY-RESET-SCH and RESET-SCHEDULE and,

DBT = the outdoor dry-bulb temperature.

Note that BON is constrained between SL and SH as well.

This quantity (QHBZ), along with its history values <QBPAST> and <QBPAST2>, are treated as another heat addition term and are added to <QNOW> and its history values <QPAST> and <QPAST2>.

The combination of these two effects produces a new expression for the value of F,

$$F = \left\{ \begin{array}{l} (<\text{TLOADS}> * \text{SIGMAG}) + \\ (<\text{QS}> + <\text{QNOW}> - <\text{QHBZ}>) + \\ [<\text{P1}> * (<\text{QSPAST}> + <\text{QPPAST}> - <\text{QNOW}> - <\text{QBPAST}>)] - \\ (\text{G1} * <\text{TNOW}>) + \\ [<\text{P2}> * (<\text{QSPAST2}> + <\text{QPAST2}> - <\text{QPAST}> - <\text{QBPAST2}>)] - \\ (\text{G2} * <\text{TPAST}>) - (\text{G3} * <\text{TPAST2}>) \end{array} \right\} . \tag{IV.348}$$

3. Correct the maximum and minimum cooling and heating rates for zone temperature change during the hour.

   Now, the maximum and minimum heat extraction and addition rates calculated for this zone in Part A of this section must be modified. This modification is done to correct these rates, which are used to determine the slope and intercept in Eq. (IV.342), for the change of zone temperature during this simulation hour. This correction is most important during warmup or cooldown periods, following a night thermostat setback or setup.

   For this correction calculation, the subroutine will assume that the temperature profile of the zone during the hour is approximated by a straight line between the starting and ending temperatures for the hour. Thus, HENOW, as an average for the hour, can be expressed as

$$\text{HENOW} = <\text{ERMAX}> - [\text{CONS}(1) * <\text{CFMAX}> * 0.5 * (<\text{TNOW}> - \text{TEND})] \tag{IV.349}$$

   where <ERMAX> is the maximum heat extraction rate for zone temperature <TNOW> and TEND is the temperature at the end of the hour.

   From Eq. (IV.344) it can be seen that

$$\mathrm{TEND} = \frac{(\mathrm{F} - \mathrm{HENOW})}{\mathrm{GO}}. \qquad \text{(IV.350)}$$

Solving Eqs. (IV.349) and (IV.350) together for TEND, yields

$$\mathrm{TEND} = \frac{(\mathrm{F} - <\mathrm{ERMAX}> + \mathrm{Y})}{(\mathrm{GO} + \mathrm{X})} \qquad \text{(IV.351)}$$

where $\mathrm{X} = \mathrm{CONS}(1) * <\mathrm{CFMAX}> * 0.5$ and
$\mathrm{Y} = \mathrm{X} * <\mathrm{TNOW}>$.

This would give a value of TEND for the zone that receives the maximum heat extraction rate for the full hour. If this is the control zone and the value produced from Eq. (IV.351) is compared to the value at the bottom of the COOL-TEMP-SCH THROTTLING-RANGE (TCZ–THR), the larger of the two values is used for TEND. Then the maximum heat extraction rate can be recalculated as

$$<\mathrm{ERMAX}> = <\mathrm{ERMAX}>_{\mathrm{old}} - [\mathrm{X} * (<\mathrm{TNOW}> - \mathrm{TEND})]. \qquad \text{(IV.352)}$$

Similarly, for the maximum heat addition rate

$$\mathrm{TEND} = (\mathrm{F} - <\mathrm{ERMIN}> + \mathrm{Y})/(\mathrm{GO} + \mathrm{X}) \qquad \text{(IV.353)}$$

where $\mathrm{X} = \mathrm{CONS}(1) * <\mathrm{CFMAXH}> * 0.5$ and
$\mathrm{Y} = \mathrm{X} * <\mathrm{TNOW}>$.

Again, if this is the control zone, the value from Eq. (IV.353) is compared to the value at the top of the HEAT-TEMP-SCH THROTTLING-RANGE (THZ + THR), and the smaller of the two values is used for TEND. Then the maximum heat addition rate can be recalculated as

$$<\mathrm{ERMIN}> = <\mathrm{ERMIN}>_{\mathrm{old}} - [\mathrm{X} * (<\mathrm{TNOW}> - \mathrm{TEND})]. \qquad \text{(IV.354)}$$

4. Calculate the hourly zone temperature and the hourly cooling and heating rates.

   a. Now that good points for the heat extraction/addition equation have been established, the zone temperature and the heat extraction/addition rates can be calculated by applying Eqs. (IV.343) and (IV.344). The subroutine (TEMDEV) starts by finding where the zone temperature would go if no extraction/addition rate was applied. This tells where the zone temperature would be at the end of the hour if no heating or cooling was supplied. From this value, TEMDEV decides whether the zone temperature will be within or below the HEAT-TEMP-SCH THROTTLING-RANGE (below THZ + THR), within a deadband, or within or above the COOL-TEMP-SCH THROTTLING-RANGE (above TCZ - THR). This test temperature (TRY) is calculated as [using Eq. (IV.344)]

$$\mathrm{TRY} = \frac{(\mathrm{F} - \mathrm{ERMAXM})}{\mathrm{GO}}. \tag{IV.355}$$

If this value of TRY falls within the deadband, the zone temperature (<TNOW>) will be TRY, and the heat extraction/addition rate (<QNOW>) will be zero. If the value of TRY falls within either the cooling or heating THROTTLING-RANGEs, the subroutine (TEMDEV) calculates the values of W and S in Eq. (IV.342) by using the top and bottom temperatures of the THROTTLING-RANGE. These values (W and S) are then substituted into Eq. (IV.343) and the value of HENOW is determined.

$$\mathrm{S} = \frac{\mathrm{ERMAX} - \mathrm{ERMIN}}{<\text{THROTTLING-RANGE}>}\text{, and} \tag{IV.356}$$

$$\mathrm{W} = \frac{\mathrm{ERMAX} + \mathrm{ERMIN}}{2.0} - (\mathrm{S} * <\mathrm{TSET}>) \tag{IV.357}$$

where

for TRY $\geq$ (TCZ - THR), that is, above the bottom of the cooling THROTTLING-RANGE,

ERMAX = <ERMAX> from Eq. (IV.352),
ERMIN = ERMAXM if occurring in a subzone, or 0.0 if occurring in a control zone, and
<TSET> = the hourly value referenced by COOL-TEMP-SCH;

for TRY $\leq$ (THZ + THR), that is, below the top of the heating THROTTLING-RANGE,

ERMAX = <ERMAX> from Eq. (IV.354) + <BASEBOARD-RATING>,
ERMIN = ERMINM (equal to ERMAXM) if occurring in a subzone, or 0.0 if occurring in a control zone, and
<TSET> = the hourly value referenced by HEAT-TEMP-SCH.

Just applying Eq. (IV.343) can produce a value for HENOW that is outside the limits of the equipment involved. It is, therefore, necessary to constrain HENOW within limits and thus, during some hours, result in a "Load Not Met". Thus, QOVER is set to the amount by which HENOW exceeds the limit.

b. If a NATURAL-VENT-AC and NATURAL-VENT-SCH have been specified, there is a possibility that cooling may be done by opening windows. If the control zone is in the venting mode, all the conditioned subzones are also assumed to be in the venting mode. For the control zone to be in the venting mode, the following must be true

(1) the value of NATURAL-VENT-AC must be greater than zero,
(2) NATURAL-VENT-SCH must be specified and the value this hour must be non-zero,
(3) the room temperature (<TNOW>) must not be above the cooling throttling range,
(4) the outdoor temperature must be less than the indoor temperature, and
(5) if the hourly value of the NATURAL-VENT-SCH is less than zero, the outdoor air enthalpy must be less than the indoor air enthalpy, as calculated from the previous hour's enthalpies.

If the above are true, the potential for cooling by natural ventilation is calculated. If the windows are fully open the entire hour, the ventilation cooling rate is given by

$$\text{HENOW} = \text{CONS}(1) * \text{<NATURAL-VENT-AC>} * \frac{\text{<volume>}}{60.0} * \left[\text{DBT} - \frac{(\text{<TNOW>} - \text{TEND})}{2.0}\right] \quad (\text{IV.358})$$

where TEND is the zone temperature at the end of the current hour.

Combining Eq. (IV.350) with Eq. (IV.358), and solving for TEND yields,

$$\text{TEND} = \frac{\text{F} - \{\text{X} * [\text{<TNOW>} - (2.0 * \text{DBT})]\}}{\text{GO} + \text{X}} \quad (\text{IV.359})$$

where

$$\text{X} = \text{CONS}(1) * \text{<NATURAL-VENT-AC>} * \frac{\text{<volume>}}{60.0} * 0.5.$$

Using Eq. (IV.358) to calculate <ERMAX> yields

$$<\mathrm{ERMAX}> = [<\mathrm{TNOW}> + \mathrm{TEND} - (2.0 * \mathrm{DBT})] * \mathrm{X}. \qquad \text{(IV.360)}$$

If a VENT-TEMP-SCH has been specified, its value for this hour is used as the desired temperature for cooling by natural ventilation. If this schedule has not been specified, the subroutine, by default, uses the top of the heating throttling range as the desired temperature. Thus, the heat extraction rate required to meet this temperature can be calculated using Eq. (IV.350) to get Eq. (IV.361)

$$\mathrm{HENOW} = \mathrm{F} - (\mathrm{T} * \mathrm{GO}), \qquad \text{(IV.361)}$$

or <ERMAX> from Eq. (IV.360), whichever is smaller,

where T = the hourly value from VENT-TEMP-SCH, if specified,

or, if not specified,

$$\mathrm{T} = \mathrm{THZ} + \frac{\text{THROTTLING-RANGE}}{2.0}\ .$$

If the value for TEND calculated by Eq. (IV.359) is above the cooling throttling range, venting is not allowed and mechanical cooling is used.

5. Simulate the thermostatically-controlled baseboards.

The value of <QNOW> is used by the air system calculation to determine the quantity of heating air. If the user has specified BASEBOARD-CTRL = THERMOSTATIC, the baseboard heaters will be activated before any other heating device, assuming this is the control zone. For subzones, the furnace heat is accounted for first and then it is supplemented to reach the heating set point with the thermostatically-controlled baseboards. Thus, the value of <QNOW> is reduced by the amount of heat provided by the baseboards (but not exceeding the baseboard capacity). Therefore, for subzones

$$\mathrm{QHBZ} = \left\{ \begin{array}{l} \text{the larger of } (<\mathrm{QNOW}> - <\mathrm{ERMAX}>) \\ \text{or } <\text{BASEBOARD-RATING}> \text{ (heating is} \\ \text{negative)} \end{array} \right\} \qquad \text{(IV.362)}$$

and

$$<\mathrm{QNOW}> = <\mathrm{QNOW}>_{old} - \mathrm{QHBZ}.$$

6. Update the zone temperature and heat addition/extraction history.

   Before returning to the air system calculation for this zone, the subroutine updates the history of <QNOW>, <TNOW>, and QHBZ. Also, the subroutine saves the current zone temperature in the TEMPS array (position 4) for use during the next hour in the internal heat transfer correction term.

7. Perform calculations for unconditioned zones.

   For zones that are UNCONDITIONED, the subroutine needs to modify the formulation shown in Step 4. In an UNCONDITIONED zone, there is no active heating or cooling. Thus, zone HENOW is set to zero and Eq. (IV.344) becomes TRY = F/GO. This value is then used as the zone temperature.

C. For the control zone, calculate the fan part load ratio.

For the control zone, the subroutine needs to calculate what fraction of the hour the furnace or air-conditioner has operated in response to the load. This fraction will be used to calculate air flow rates for the conditioned subzones. For cooling,

$$\mathrm{PLRC} = \frac{\langle \mathrm{QNOW} \rangle}{\langle \mathrm{ERMAX} \rangle} \text{ or 0.0, whichever is larger.} \qquad \text{(IV.363)}$$

For heating,

$$\mathrm{PLRH} = \frac{\langle \mathrm{QNOW} \rangle}{\langle \mathrm{ERMIN} \rangle} \text{ or 0.0, whichever is larger.} \qquad \text{(IV.364)}$$

D. Sum the necessary information for the simulation of the central HVAC unit.

To obtain system level performance data, several quantities need to be summed over all the zones. These include baseboard energy,

$$\mathrm{QHB} = \sum_{nz=1}^{nzones} \mathrm{QHBZ}_{nz} * \mathrm{MULTIPLIER}_{nz}, \qquad \text{(IV.365)}$$

electrical energy,

$$\langle \mathrm{SKW} \rangle = \sum_{nz=1}^{nzones} \langle \mathrm{ZKW} \rangle_{nz} * \mathrm{MULTIPLIER}_{nz}, \qquad \text{(IV.366)}$$

infiltration air flow rate,

$$CINF = \sum_{nz=1}^{nzones} \langle CFMINF \rangle_{nz} * MULTIPLIER_{nz}, \text{ and} \tag{IV.367}$$

space latent heat gain from people and equipment,

$$QLSUM = \sum_{nz=1}^{nzones} \langle QL \rangle_{nz} * MULTIPLIER_{nz}. \tag{IV.368}$$

II. Simulate the central HVAC unit performance

A. If the HVAC unit has a dual speed compressor, determine if it is running at high speed or low speed.

If COMPRESSOR-TYPE = DUAL-SPEED, the subroutine first determines whether the unit is operating at the high or low speed. If the net load on the unit (Q) is less than zero (indicating a heating load) and the magnitude of the load is less than the capacity of the unit at the low speed, the subroutine assumes that the unit is operating at its low speed. Similarly, if the net load on the unit (Q) is greater than zero (indicating a cooling load) and the magnitude is less than the cooling capacity of the unit at the lower speed, the subroutine assumes that the unit is operating at its lower speed. If the unit is operating in low speed (either heating or cooling), the values for LSR(1) through LSR(4) are set equal to the values for LOW-SPEED-RATIOS; otherwise, LSR(1) through LSR(4) are set equal to 1.0.

The net load on the unit is

$$Q = \left\{ \begin{array}{l} CONS(1) * SUPPLY\text{-}CFM * \\ [TM - (THMAX + DUCT\text{-}DELTA\text{-}T)] * \\ PLRH, \text{ if } PLRH > 0.0 \\ \\ \text{or} \\ \\ CONS(1) * SUPPLY\text{-}CFM * \\ [TM - (TCMIN - DUCT\text{-}DELTA\text{-}T)] * \\ PLRC, \text{ if } PLRC > 0.0 \end{array} \right\} . \tag{IV.369}$$

B. Simulate the central HVAC unit.

If the central unit is in the venting mode, or PLRH and PLRC are both zero, no heating or cooling energy is supplied from the central unit.

1. The Cooling Mode

If PLRC is not zero, the central air conditioner is running some part of the hour. The air flow rate (CFM) is calculated from the part load ratio

$$CFM = SUPPLY\text{-}CFM * PLRC. \tag{IV.370}$$

The subroutine then determines if the coil is wet or dry. The contact between the cooling coil and the mixed air is characterized by the coil bypass factor (CBF). This value is assumed to be a product of the design (rated) bypass factor and two modifier functions to correct for off-rated conditions

$$CBF = \begin{Bmatrix} COIL\text{-}BF * \\ CVAL(COIL\text{-}BF\text{-}FT,EWB,T) * \\ CVAL(COIL\text{-}BF\text{-}FCFM,PLRCFM) \end{Bmatrix} \tag{IV.371}$$

where

COIL-BF-FT is a correction function to the coil bypass factor to adjust for off-rated entering wet-bulb temperature (EWB) and entering dry-bulb temperature (T),

COIL-BF-FCFM is a correction function to the coil bypass factor to adjust for off-rated air flow rate caused by part load operation (PLRCFM),

EWB = the past hour's entering wet-bulb temperature and

PLRCFM = SUPPLY-CFM / RATED-CFM.

To perform a moisture balance on the room, the subroutine needs to know the coil surface conditions of temperature (TSURF) and humidity ratio (WSURF). The temperature is calculated by using the bypass relationship

$$TSURF = \frac{TC - (CBF * TM)}{1.0 - CBF} \tag{IV.372}$$

where TC is the supply air temperature during the time that the compressor is operating, that is, TC = TCMIN – DUCT-DELTA-T.

The coil surface humidity ratio at saturation (WSURF) is calculated at the temperature TSURF and atmospheric pressure. A moisture balance on the space, equating gains and losses, is expressed as

$$(CFM * WCOIL) + (CINF * HUMRAT) + \Delta W = (CFM * WR) + (CINF * WR) \tag{IV.373}$$

where WCOIL = coil exit humidity ratio,
WR = space humidity ratio, and
ΔW = QLSUM/CONS(2), the space latent heat gain from people plus equipment.

By defining F = CINF/CFM and DW = ΔW/CFM, and rearranging Eq. (IV.373), WR becomes

$$WR = \frac{WCOIL + DW + (F * HUMRAT)}{1.0 + F} . \tag{IV.374}$$

It is also known that the mixed air humidity ratio is equal to the room air humidity ratio. Thus, assuming no moisture condensation on the cooling coil (that is, WCOIL = WM) leads to

$$WM = HUMRAT + \frac{DW}{F}. \tag{IV.375}$$

If the amount of infiltration air is zero, the right-hand side of the above equation becomes (HUMRAT + DW). If the value of WM is less than WSURF, the coil is dry and there is only a need to calculate the sensible cooling load (with no latent load, the sensible load is the total load)

$$QC = [TM - (TCMIN - DUCT\text{-}DELTA\text{-}T)] * CONS(1) * SUPPLY\text{-}CFM * PLRC. \tag{IV.376}$$

If the calculated mixed air humidity ratio is larger than the coil surface humidity ratio at saturation, condensation will take place. The bypass relationship (CBF) relates coil entering and exiting conditions

$$WCOIL = (CBF * WM) + [(1.0 - CBF) * WSURF]. \tag{IV.377}$$

Combining Eqs. (IV.374) and (IV.377) gives

$$WR = \frac{[(1.0 - CBF) * WSURF] + DW + (F * HUMRAT)}{1.0 + F - CBF} \tag{IV.378}$$

and by reapplying Eq. (IV.377), WCOIL is calculated. The sensible part of the cooling coil load is calculated as in Eq. (IV.376), with the latent cooling load as an additional load

$$QCLAT = (WM - WCOIL) * CONS(2) * SUPPLY\text{-}CFM * PLRC \tag{IV.379}$$

$$QC = \Big\{[TM - (TCMIN - DUCT\text{-}DELTA\text{-}T)] * CONS(1) * SUPPLY\text{-}CFM * PLRC\Big\} + QCLAT. \tag{IV.380}$$

The coil entering wet-bulb temperature (EWB) is then calculated at TM, WM, and the atmospheric pressure (PATM).

It is necessary next to calculate the compressor energy input. First, the capacity (QCT) is recalculated so that the energy estimate is as close as possible. The electric input ratio (EIR) is assumed to be the product of the design (rated) EIR and two modifier functions, one to correct for off-design temperatures and the other to correct for compressor part load effects

$$EIR = COOLING\text{-}EIR * CVAL(COOL\text{-}EIR\text{-}FT,EWB,T) * CVAL(COOL\text{-}EIR\text{-}FPLR,PLRCC) * LSR(2) \tag{IV.381}$$

where PLRCC = QC/QCT.

Then, the unit electrical consumption (QCKW) can be calculated as

$$SQCKW = QCT * EIR * 0.000293,$$

where 0.000293, or 1/3413, converts Btu/hr to kilowatt-hr.

The total electrical energy consumed is the sum of the LOADS electrical, the compressor electrical, and the air fan electrical energy consumptions.

2. The Heating Mode

If PLRH is greater than zero, the unit is in the heating mode. The supply air flow rate (CFM) and the supply air fan electrical consumption (SKFW) are calculated by using this part load ratio; that is,

$$CFM = SUPPLY\text{-}CFM * PLRH \text{ and} \qquad SKFW = SUPPLY\text{-}KW * PLRH. \tag{IV.382}$$

From Eq. (IV.375), it is possible to calculate the mixed air humidity ratio and thus, the wet-bulb temperature. If the HEAT-SOURCE has been specified as HOT-WATER or HOT-WATER/SOLAR, the heating energy is calculated as

$$QH = [TM - (THMAX + DUCT\text{-}DELTA\text{-}T)] * CONS(1) * SUPPLY\text{-}CFM * PLRH. \tag{IV.383}$$

If the HEAT-SOURCE has been specified as GAS-FURNACE (the default) or OIL-FURNACE, the subroutine FURNAC is called to simulate the furnace.

If the HEAT-SOURCE has been specified as HEAT-PUMP, a more complicated simulation must be performed. First, the heat pump capacity (QHPT) is recalculated, knowing the actual room temperature and adjusting for any defrosting. QHPT is recalculated as defined in Eq. (IV.335). The defrosting fraction of the hour (EIRM3) is defined by the curve DEFROST-DEGRADE. There is no default curve for DEFROST-DEGRADE; the user must input it using the CURVE-FIT instruction.

This curve provides the ratio of defrost time to heating time, as a function of outdoor wet-bulb and dry-bulb temperatures.

$$\begin{aligned} EIRM3 &= CVAL(DEFROST\text{-}DEGRADE,WBT,DBT), \text{ however,} \\ &= 0.0, \text{ if } DBT > DEFROST\text{-}T. \end{aligned} \tag{IV.384}$$

The part of the heating load attributed to the electric resistance heater (Q) is that portion of the load above the heat pump capacity (QHPT). This is the entire heating load if the outdoor dry-bulb temperature is less than MIN-HP-T

$$Q = QH - [QHPT * LSR(3) * (1.0 - EIRM3)]. \tag{IV.385}$$

The heating load on the heat pump (QHP) is that portion of QH not met by Q, but not exceeding the heating capacity of the heat pump (QHPT)

$$QHP = QH - Q. \tag{IV.386}$$

The defrost load (QD) is the defrost run fraction (EIRM3) times the available capacity

$$QD = EIRM3 * \frac{QHP}{QHPT} * QHPT. \tag{IV.387}$$

The operating electric input ratio (EIR) for this hour is the design (or rated) HEATING-EIR multiplied by three modifier functions, one for off-design temperatures, one for off-design loading, and one for off-design CFM

$$\begin{aligned} EIR = \; & \text{HEATING-EIR} * \text{CVAL(HEAT-EIR-FT,DBT,TM)} \\ & * \text{CVAL(HEAT-EIR-FPLR,PLRH)} * \text{LSR(2)} \\ & * \text{CVAL(RATED-HEIR-FCFM,PLRCFM)} \end{aligned} \qquad \text{(IV.388)}$$

where

$$PLRH = \frac{QHP + QD}{QHPT}$$ (assuming the defrost EIR and the space heat mode are approximately equal) and

$$PLRCFM = \frac{\text{SUPPLY-CFM}}{\text{RATED-CFM}} .$$

The total electrical energy consumption is the sum of the electrical consumption calculated by LOADS plus the compressor energy (including defrost), the electric resistance heat, and the fan energy consumptions

$$\langle SKW \rangle = \sum_{nz=1}^{nzones} \left(\langle ZKW \rangle_{nz} * MULTIPLIER_{nz} \right) + SQHKW + SFKW \qquad \text{(IV.389)}$$

where $SQHKW = - [(QHPT * EIR) + (Q + QD)] * 0.000293.$

C. Save all quantities that would be needed for a solar equipment simulation.

If the HEAT-SOURCE has been specified as HOT-WATER/SOLAR, the program calculates, at the PLANT level, the total heating coil load (QHMP), the total air flow rate (CFMP), and the average coil air entering temperature (TMP). These calculated values are saved for use by the solar simulator

$$QHMP = \sum_{ns=1}^{nsystems} QH_{ns}, \qquad \text{(IV.390)}$$

$$CFMP = \sum_{ns=1}^{nsystems} CFM_{ns}\text{, and} \tag{IV.391}$$

$$TMP = \frac{\sum_{ns=1}^{nsystems} TM_{ns} * CMF_{ns}}{CFMP}\ . \tag{IV.392}$$

3.2 Unitary Systems

3.2.1 Fan Coil Units (subroutines FCOIL and SDSF)

Subroutine FCOIL, together with the single-duct air-handler subroutine (SDSF), simulates the heat and moisture exchange for constant-volume, variable-temperature, chilled-water, two- and four-pipe fan coil systems (SYSTEM-TYPE = TPFC and FPFC). The simulation of these systems uses utility subroutines, described later, to calculate room air temperature and heat extraction/addition rate (subroutine TEMDEV), and fan power consumption (subroutine FANPWR). The single-duct air-handler simulation (subroutine SDSF) is used to simulate each individual fan coil unit.

Calculation Outline

For each zone attached to this system,

A. calculate the maximum cooling and heating rates,

B. calculate the hourly zone temperature and the hourly heat addition/extraction rate (subroutine TEMDEV),

C. calculate the fan coil unit performance (subroutine SDSF), and

D. save all quantities that would be needed for a solar system simulation.

Calculation Algorithms

In these SYSTEM-TYPEs, there is no central air handling unit, but rather individual units in each zone. The subroutines will simulate the zone unit for all the zones attached to this system.

A. Calculate the maximum cooling and heating rates.

The first step is to calculate the maximum cooling and heating rates for each zone. This is done by calculating the air temperature entering the coil(s) and then, using the capacity of the unit, calculate the minimum and maximum coil exit air conditions.

To calculate the mixed air temperature (TM), it is necessary to know the fraction (PO) of outside ventilation air in the total air supply. PO is calculated as the larger of the outside ventilation air, needed to compensate for exhaust air, or the value calculated from other zone- or system-level keywords.

$$PO = \frac{\text{OUTSIDE-AIR-CFM}}{\text{<CFMAX>}}, \text{ if OUTSIDE-AIR-CFM has been specified.} \quad (IV.393)$$

Otherwise,

$$PO = \text{the larger of } \frac{\text{OA-CHANGES} * \langle\text{VOLUME}\rangle}{60.0 * \langle\text{CFMAX}\rangle} \text{ and}$$

$$\frac{\text{OA-CFM/PER} * \langle\text{PEOPLE}\rangle}{\langle\text{CFMAX}\rangle}\text{, rounded up to the nearest 10 cfm.}$$

If no value has been specified for OUTSIDE-AIR-CFM, OA-CHANGES, or OA-CFM/PER,

$$PO = \text{MIN-OUTSIDE-AIR.}$$

However, if MIN-AIR-SCH has been specified,

$$PO = \text{the hourly value referenced by MIN-AIR-SCH.}$$

If PO has not been given a positive value at this point, it defaults to zero. After the value of PO has been determined, as above, it is tested to ensure that it is greater than the fraction of exhaust air. Therefore,

$$PO = \frac{\text{EXHAUST-CFM}}{\langle\text{CFMAX}\rangle}\text{, if larger than any of the above.}$$

The air temperature entering the coils may now be estimated by using PO and the past hour's room air temperature (<TNOW>)

$$TM = (PO * DBT) + [(1.0 - PO) * \langle\text{TNOW}\rangle] + \text{SUPPLY-DELTA-T.} \tag{IV.394}$$

The total and sensible cooling capacities (QCT and QCS respectively) are calculated by using the current hour's entering dry-bulb temperature and the past hour's entering wet-bulb temperature (<PASTWBZ>).

$$QCT = \langle\text{COOLCAPZ}\rangle * \text{CVAL(COOL-CAP-FT,EWB,T) and} \tag{IV.395}$$

$$QCS = \text{the smaller of } [\langle\text{COOLSHZ}\rangle * \text{CVAL(COOL-SH-FT,EWB,T)}] \text{ and } QCT \tag{IV.396}$$

where EWB is the larger of <PASTWBZ> and 60.0. T is the larger of COOL-FT-MIN and TM. The value of COOL-CAP-FT is a correction function to the total cooling capacity to adjust for off-rated entering wet-bulb temperature (EWB) and entering dry-bulb temperature (T). The value of COOL-SH-FT is a correction function to the sensible cooling capacity to adjust for off-rated entering wet-bulb temperature and entering dry-bulb temperature.

Thus, the minimum zone supply air temperature (TCMINZ) can be calculated as

$$\text{TCMINZ} = \text{TM} - \frac{\text{QCS} * \text{CON}}{\text{CONS(1)} * \text{<CFMAX>}} \qquad \text{(IV.397)}$$

or

$$\text{MIN-SUPPLY-T} - \frac{\text{THROTTLING-RANGE}}{2.0}, \text{ whichever is larger.}$$

CON is a cooling flag. If CON = 0, cooling is off; if CON = 1, cooling is on.

The maximum cooling rate (<ERMAX>) is then calculated

$$\text{<ERMAX>} = \text{CONS(1)} * \text{<CFMAX>} * (\text{<TNOW>} - \text{TCMINZ}). \qquad \text{(IV.398)}$$

The cooling rate within the deadband of the thermostat (ERMAXM) is calculated by assuming that mixed air is flowed into the zone

$$\text{ERMAXM} = \text{CONS(1)} * \text{<CFMAX>} * (\text{<TNOW>} - \text{TM}). \qquad \text{(IV.399)}$$

The maximum supply air temperature is calculated by using the heating capacity of the unit

$$\text{THMAXZ} = \text{TM} - \frac{\text{<HEATCAPZ>} * \text{HON}}{\text{CONS(1)} * \text{<CFMAX>}} \qquad \text{(IV.400)}$$

or MAX-SUPPLY-T,

whichever is smaller.

HON is a heating flag. If HON = 0, heating is off; if HON = 1, heating is on. The maximum heat addition rate (<ERMIN>) is calculated as

$$\text{<ERMIN>} = \text{CONS(1)} * \text{<CFMAX>} * (\text{<TNOW>} - \text{THMAXZ}). \qquad \text{(IV.401)}$$

B. Calculate the hourly zone temperature and the hourly heat addition/extraction rate.

The subroutine TEMDEV is called to calculate the room air temperature at the end of the hour and the net room heat extraction/addition rate for the hour (<QNOW>). The average room air temperature for this hour (TAVE) is calculated as the average of the temperature at the end of the past hour (<TPAST>) and the temperature this hour (<TNOW>)

$$TAVE = \frac{<TPAST> + <TNOW>}{2}.$$

All zone coil load calculations will be based upon TAVE.

C. Calculate the fan coil unit performance (subroutine SDSF).

The supply air temperature needed for this zone (TC) is calculated as

$$TC = TAVE - \frac{<QNOW>}{CONS(1) * <CFMAX>} \tag{IV.402}$$

or TM, if TAVE is within the deadband of the thermostat.

The subroutine SDSF (see Sec. 3.1.2 of this chapter) is called to simulate the performance of the fan coil unit in this zone.

Several quantities are summed for all zones including

exhaust fan energy consumption,

$$FANKW = \sum_{nz=1}^{nzones} EXHAUST\text{-}KW_{nz} * MULTIPLIER_{nz}, \tag{IV.403}$$

baseboard heater energy consumption,

$$QHB = \sum_{nz=1}^{nzones} QHBZ_{nz} * MULTIPLIER_{nz}, \tag{IV.404}$$

total zone heating coil energy consumption,

$$QHZ = \sum_{nz=1}^{nzones} QH_{nz} * MULTIPLIER_{nz}, \qquad (IV.405)$$

total zone cooling coil energy consumption,

$$QCZ = \sum_{nz=1}^{nzones} QC_{nz} * MULTIPLIER_{nz}, \qquad (IV.406)$$

and total electrical energy consumption,

$$<SKW> = \sum_{nz=1}^{nzones} (<ZKW>_{nz} + EXHAUST\text{-}KW_{nz}) * MULTIPLIER_{nz}. \qquad (IV.407)$$

D. Save all quantities that would be needed for a solar system simulation.

If the HEAT-SOURCE = HOT-WATER/SOLAR, the total (SYSTEM level) zone heating coil load, the total air flow rate, and the average coil entering air temperature are saved to be passed later to the solar simulator in the PLANT program,

$$QHZP = QHZ, \qquad (IV.408)$$

$$CFMZP = \sum_{nz=1}^{nzones} <CFMAX>_{nz} * MULTIPLIER_{nz}, \text{ and} \qquad (IV.409)$$

$$TZP = \frac{\sum_{nz=1}^{nzones} TC_{nz} * <CFMAX>_{nz} * MULTIPLIER_{nz}}{CFMZP}. \qquad (IV.410)$$

3.2.2. Water-to-Air California Heat Pump (subroutine HTPUMP)

This subroutine simulates the heat and moisture exchange of a water-to-air (California) heat pump system; that is, when SYSTEM-TYPE = HP. This simulation utilizes the room air temperature and the heat addition/extraction rate calculations (subroutine TEMDEV). The basic components of this system are a pipe loop with a circulating fluid that is utilized as a heat source and heat sink and individual water-to-air heat pump units in each zone connected to the system. Under the correct conditions, this system transports heat from those zones that do not need heat to those zones that do; therefore, this system, to be advantageous, should be used in buildings with more than one zone.

Calculation Outline

I. For each zone connected to this system

A. calculate the maximum cooling and heating rates,

B. calculate the hourly room air temperature and the hourly heat addition/ extraction rate (subroutine TEMDEV), and

C. simulate the zone heat pump performance,

1. in the cooling mode, and
2. in the heating mode.

II. Simulate the central fluid loop

A. Calculate the temperature of the fluid in the loop and, if required, any heating or cooling of the loop fluid.

Calculation Algorithms.

I. For each zone connected to this system, calculate the performance of the equipment in the zone, as well as the zone conditions

This SYSTEM-TYPE has no central air handling unit, but rather it has individual units in each conditioned zone connected to the system. The subroutine performs a simulation of each zone unit separately.

A. Calculate the maximum cooling and heating rates.

To calculate the cooling or heating load on each unit, it is necessary to first calculate the unit's capacity this hour so that subroutine TEMDEV can be used to simulate the thermostat action and the resultant heat addition/extraction rate. By calculating, for the current hour, the unit's air and liquid coil entering conditions and the resultant cooling and heating capacities, the maximum and minimum coil exit air conditions can be calculated. From this, the maximum and minimum extraction rates can be calculated.

To calculate the mixed air temperature (TM), the subroutine must know the fraction (PO) of outside ventilation air in the total supply air. This fraction (PO) is calculated from the value specified for certain zone or system level keywords

$$PO = \frac{\text{OUTSIDE-AIR-CFM}}{<\text{CFMAX}>}, \text{ if OUTSIDE-AIR-CFM has been specified.} \qquad \text{(IV.411)}$$

Otherwise,

$$PO = \text{the larger of } \frac{\text{OA-CHANGES * VOLUME}>}{60.0 * <\text{CFMAX}>} \text{ and } \frac{\text{OA-CFM/PER * }<\text{PEOPLE}>}{<\text{CFMAX}>},$$

rounded to nearest 10 CFM.

If no value has been specified for OUTSIDE-AIR-CFM, OA-CHANGES, or OA-CFM/PER,

PO = MIN-OUTSIDE-AIR.

However, if MIN-AIR-SCH has been specified,

PO = the hourly value referenced by MIN-AIR-SCH.

If PO has not been given a value by any of the preceeding specifications, it defaults to zero.

The air temperature entering the coil is now estimated by using PO and the past hour's room air temperature (<TNOW>).

$$TM = (PO * DBT) + [(1.0 - PO) * <\text{TNOW}>] + \text{SUPPLY-DELTA-T}. \qquad \text{(IV.412)}$$

The total and sensible cooling capacities (QCT and QCS respectively) are calculated by using the coil entering fluid temperature (calculated from the previous hour's average leaving fluid temperature), as well as the coil entering dry-bulb and wet-bulb air temperatures. The entering wet-bulb temperature for the previous hour is used in this cooling capacity estimate for the current hour

$$QCT = <\text{COOLCAPZ}> * \text{CVAL(COOL-CAP-FT,EWB,}<\text{FLUIDT}>\text{) and} \qquad \text{(IV.413)}$$

$$QCS = \text{the smaller of } \{[\text{<COOLSHZ>} * \text{CVAL(COOL-SH-FT,EWB,<FLUIDT>)}] + [\text{CONS(1)} * \text{<CFMAX>}] * (1.0 - \text{COIL-BF}) * (TM - 80.0)\}$$

and QCT

where EWB is the larger of <PASTWBZ> and 60.0. <FLUIDT> is the calculated loop temperature for the past hour. The value of COOL-CAP-FT is a correction function to the total cooling capacity to adjust for off-rated entering wet-bulb temperature (EWB) and entering fluid temperature (<FLUIDT>). The value of COOL-SH-FT is a correction function to the sensible cooling capacity to adjust for off-rated entering wet-bulb temperature and entering fluid temperature.

Thus, the minimum zone supply air temperature (TCMINZ) can be calculated,

$$TCMINZ = TM - \frac{QCS * CON}{\text{CONS(1)} * \text{<CFMAX>}} \qquad \text{(IV.414)}$$

or

$$\text{MIN-SUPPLY-T} - \frac{\text{THROTTLING-RANGE}}{2.0}, \text{ whichever is larger.}$$

CON is a cooling flag. If CON = 0, cooling if off; if CON = 1, cooling is on.

The maximum cooling rate (<ERMAX>) is then calculated as

$$\text{<ERMAX>} = \text{CONS(1)} * \text{<CFMAX>} * (\text{<TNOW>} - TCMINZ). \qquad \text{(IV.415)}$$

If the zone temperature is within the deadband of the thermostat, and this unit runs continuously because of an outside ventilation air requirement ($PO \neq 0$), the heat extraction rate from mixed air is calculated as

$$ERMAXM = \text{CONS(1)} * \text{<CFMAX>} * (\text{<TNOW>} - TM). \qquad \text{(IV.416)}$$

Otherwise, this value is zero because the unit cycles with the zone load.

In a similar manner, the heating capacity (QHT), the maximum supply air temperature (THMAXZ), and the maximum heat addition rate (<ERMIN>) may be calculated

$$QHT = \text{<HEATCAPZ>} * \text{CVAL(HEAT-CAP-FT,<TNOW>,<FLUIDT>)}, \qquad \text{(IV.417)}$$

$$THMAXZ = TM - \frac{QHT * HON}{CONS(1) * \langle CFMAX \rangle} \text{ , and} \qquad (IV.418)$$

$$\langle ERMIN \rangle = CONS(1) * \langle CFMAX \rangle * (\langle TNOW \rangle - THMAXZ) \qquad (IV.419)$$

where HEAT-CAP-FT is a correction function to the total heating capacity to adjust for off-rated entering dry-bulb temperature (<TNOW>) and entering fluid temperature (<FLUIDT>).

HON is a heating flag. If HON = 0, heating is off; if HON = 1, heating is on.

B. Calculate the hourly room air temperature and the hourly heat addition/extraction rate.

The subroutine TEMDEV is called to calculate the room air temperature at the end of the current hour and the net heat extraction/addition rate during the hour (<QNOW>). The average room air temperature for this hour (TAVE) is calculated as the average air temperature at the end of the past hour (<TPAST>) and the temperature this hour (<TNOW>)

$$TAVE = \frac{\langle TPAST \rangle + \langle TNOW \rangle}{2}.$$

TAVE will be used in all subsequent zone coil load calculations.

C. Simulate the zone heat pump performance.

The heat pump performance can now be simulated. First, the net load on the unit is calculated to determine whether it is in the heating or the cooling mode. First, the net sensible cooling (or heating) load on the unit is calculated

$$Q = \langle QNOW \rangle + [CONS(1) * \langle CFMAX \rangle * (TAVE - TM)] \qquad (IV.420)$$

where

$$TM = (PO * DBT) + [(1.0 - PO) * TAVE] + SUPPLY\text{-}DELTA\text{-}T.$$

Then the supply air temperature (TS) leaving the unit is calculated as

$$TS = TAVE - \frac{\langle QNOW \rangle}{CONS(1) * \langle CFMAX \rangle} \text{ if } PO \neq 0.0\text{, but} \qquad (IV.421)$$

$$TS = TM - \frac{F}{CONS(1) * <CFMAX>} \text{ if } PO = 0.0,$$

where F = QCS if Q > 0.0 and F = QHT if $Q \leq 0.0$.

TS = TM, if TAVE is within the deadband of the thermostat.

If TM is equal to TS, no compressor energy is required. Also, if TM = TS and no outside ventilation air is required (PO = 0.0), no fan energy is required. If outside ventilation air is required (PO > 0.0), the heating and cooling air flow rates (FH and FC respectively) are each set to half the design air flow rate (<CFMAX>).

1. The Cooling Mode

If TM is larger than TS, the unit is in the cooling mode. If outside ventilation air is required (PO > 0.0), the fans run continuously. If no outside air is required (PO = 0.0), the fans will cycle with the compressor to meet the cooling load. Thus, the cooling supply air flow rate (FC) is calculated as

$$FC = <CFMAX>, \text{ if } PO > 0.0 \tag{IV.422}$$

and

$$FC = \frac{<QNOW>}{<ERMAX>} * <CFMAX>, \text{ if } PO = 0.0.$$

Next, it is determined if the coil is wet or dry. The contact between the cooling coil and the mixed air is characterized by the coil bypass factor (CBF). This value is assumed to be the product of the design (rated) bypass factor (COIL-BF) and two modifier functions to adjust for off-design conditions

$$\begin{aligned} CBF = {} & COIL\text{-}BF * CVAL(COIL\text{-}BF\text{-}FT, EWB, <FLUIDT>) \\ & * CVAL(COIL\text{-}BF\text{-}FCFM, PLRCFM) \end{aligned} \tag{IV.423}$$

where

COIL-BF-FT is a correction function to the coil bypass factor to adjust for off-rated entering wet-bulb temperature (EWB) and entering fluid temperature (<FLUIDT>), COIL-BF-FCFM is a correction function to adjust for off-rated air flow rate caused by part load operation (PLRCFM),

EWB = the past hour's entering wet-bulb temperature, and

$$PLRCFM = \frac{<CFMAX>}{RATED\text{-}CFM}.$$

To perform a moisture balance on the room, the subroutine needs to know the cooling coil surface conditions of temperature (TSURF) and humidity ratio (WSURF). TSURF is calculated by using the bypass relationship

$$TSURF = \frac{TC - (CBF * TM)}{1.0 - CBF} \qquad (IV.424)$$

where TC is the supply air temperature leaving the coil during the time the compressor is operating.

$$TC = TM - \frac{QCS}{CONS(1) * <CFMAX>}\text{, or} \qquad (IV.425)$$

$$MIN\text{-}SUPPLY\text{-}T - \frac{THROTTLING\text{-}RANGE}{2.0},$$

whichever is larger.

The coil surface humidity ratio (WSURF) is calculated at TSURF and the outdoor atmospheric pressure. A moisture balance on the space, equating gains and losses, is expressed as

$$(FC * WCOIL) + (<CFMINF> * HUMRAT) + \Delta W = (FC * WR) + (<CFMINF> * WR) \qquad (IV.426)$$

where WCOIL = coil exit air humidity ratio,
<CFMINF> = infiltration air flow rate,
HUMRAT = outside air humidity ratio,
WR = room humidity ratio, and
ΔW = <QL>/CONS(2), the space latent gain from people and equipment.

By defining

$$F = \frac{<\text{CFMINF}>}{\text{FC}} \text{ and } \text{DW} = \frac{\Delta \text{W}}{\text{FC}} ,$$

and rearranging Eq. (IV.426), WR becomes

$$\text{WR} = \frac{\text{WCOIL} + \text{DW} + (\text{F} * \text{HUMRAT})}{1.0 + \text{F}}. \tag{IV.427}$$

It is also known that the mixed air humidity ratio (WM) is

$$\text{WM} = (\text{PO} * \text{HUMRAT}) + [(1.0 - \text{PO}) * \text{WR}]. \tag{IV.428}$$

Combining Eqs. (IV.427) and (IV.428), and assuming no moisture condensation on the cooling coil (that is, WCOIL = WM), yields

$$\text{WM} = \text{HUMRAT} + \left\{\left[\frac{(1.0 - \text{PO})}{(\text{F} + \text{PO})}\right] * \text{DW}\right\}. \tag{IV.429}$$

If the amount of outside ventilation air plus infiltration air is zero, the right-hand side of the above equation is replaced with (HUMRAT + DW.) If the value of WM is less than WSURF, the coil is dry and it is necessary only to calculate the sensible cooling load (with no latent load, the sensible load is the total load)

$$\text{ZQC} = (\text{TM} - \text{TS}) * \text{CONS}(1) * \text{FC}. \tag{IV.430}$$

If the calculated mixed air humidity ratio is larger than the coil surface humidity ratio at saturation, condensation will take place. The bypass relationship (CBF) relates coil entering and exiting humidity ratios

$$\text{WCOIL} = (\text{CBF} * \text{WM}) + [(1.0 - \text{CBF}) * \text{WSURF}]. \tag{IV.431}$$

Combining Eqs. (IV.427), (IV.428), and (IV.431), gives

$$\text{WR} = \frac{(\text{CBF} * \text{PO} * \text{HUMRAT}) + [(1.0 - \text{CBF}) * \text{WSURF}] + \text{DW} + (\text{F} * \text{HUMRAT})}{1.0 + \text{F} - [\text{C3F} * (1.0 - \text{PO})]} \tag{IV.432}$$

and by reapplying Eqs. (IV.428) and (IV.431), WM and WCOIL are calculated. The sensible part of the cooling coil load is calculated as in Eq. (IV.430), with the latent cooling load (QCLATZ) as an additional load

$$\mathrm{QCLATZ} = (\mathrm{WM} - \mathrm{WCOIL}) * \mathrm{CONS}(2) * \mathrm{FC}. \tag{IV.433}$$

The total cooling load, sensible plus latent, for the zone (ZQC) is then

$$\mathrm{ZQC} = [(\mathrm{TM} - \mathrm{TS}) * \mathrm{CONS}(1) * \mathrm{FC}] + \mathrm{QCLATZ}. \tag{IV.434}$$

The coil entering air wet-bulb temperature (EWB) is then calculated at TM, WM, and the atmospheric pressure (PATM).

It is necessary next to calculate the compressor energy input. First, the hourly cooling capacity (QCT) of the heat pump is recalculated so that the energy estimate is as close as possible. The electric input ratio (EIR) is assumed to be the product of the design (rated) EIR and three modifier functions, one for off-design temperatures, another for compressor part load effects, and the last for off-design air flow rate

$$\begin{aligned} \mathrm{EIR} = {} & \mathrm{COOLING\text{-}EIR} * \mathrm{CVAL}(\mathrm{COOL\text{-}EIR\text{-}FT}, \mathrm{EWB}, \mathrm{FLUIDT}) \\ & * \mathrm{CVAL}(\mathrm{COOL\text{-}EIR\text{-}FPLR}, \mathrm{PLRC}) \\ & * \mathrm{CVAL}(\mathrm{RATED\text{-}CEIR\text{-}FCFM}, \mathrm{CFMPLR}) \end{aligned} \tag{IV.435}$$

where PLRC = ZQC/QCT and CFMPLR = FC / RATED-CFM.

The total electrical energy consumed in this zone (ZKW) is the sum of the LOADS electrical, the compressor electrical, and the fan electrical energy consumptions

$$\mathrm{ZKW} = \langle \mathrm{ZKW} \rangle + (\mathrm{EIR} * \mathrm{QCT} * 0.000293) + (\mathrm{FC} * \langle \mathrm{SUPPLY\text{-}KW} \rangle), \tag{IV.436}$$

where 0.000293 (or 1/3413) converts Btu/hr to kilowatt-hr.

2. The Heating Mode

If TM is less than TS, the unit is in the heating mode. Again, if outside ventilation air is required (PO > 0.0), the fans run continuously. If no outside ventilation air is required (PO = 0.0), the fans cycle with the compressor to meet the heating load. Thus, the heating air flow rate (FH) is calculated as

$$\mathrm{FH} = \mathrm{<CFMAX>}, \text{ if } \mathrm{PO} > 0.0 \text{ and} \tag{IV.437}$$

$$\mathrm{FH} = \frac{\mathrm{<QNOW>}}{\mathrm{<ERMIN>}} * \mathrm{<CFMAX>}, \text{ if } \mathrm{PO} = 0.0. \tag{IV.438}$$

From Eq. (IV.429) the mixed air humidity ratio and the mixed air wet-bulb temperature can be calculated. The hourly zone heating load is calculated as

$$\mathrm{ZQH} = (\mathrm{TM} - \mathrm{TS}) * \mathrm{CONS}(1) * \mathrm{FH}. \tag{IV.439}$$

The hourly heating capacity (QHT) of the heat pump is recalculated for a better energy input estimate. The electric input ratio (EIR) is assumed to be the product of the design (rated) EIR and three modifier functions, one for off-design temperatures, one for compressor part load effects, and one for off-design air flow rate.

$$\begin{aligned} \mathrm{EIR} = {} & \mathrm{HEATING\text{-}EIR} * \mathrm{CVAL(HEAT\text{-}EIR\text{-}FT,TM,FLUIDT)} \\ & * \mathrm{CVAL(HEAT\text{-}EIR\text{-}FPLR,PLRH)} \\ & * \mathrm{CVAL(RATED\text{-}HEIR\text{-}RCFM,PLRCFM)} \end{aligned} \tag{IV.440}$$

where PLRH = QHZ/QHT and PLRCFM = FH / RATED-CFM.

Again, the total electrical energy consumed in this zone (ZKW) is the sum of the LOADS electrical, the compressor electrical, and the fan electrical energy consumptions

$$\mathrm{ZKW} = \mathrm{<ZKW>} + (\mathrm{EIR} * \mathrm{QHT} * 0.000293) + (\mathrm{FH} * \mathrm{<SUPPLY\text{-}KW>}), \tag{IV.441}$$

where 0.000293 (or 1/3413) converts Btu/hr to kilowatt-hr.

II. Simulate the central fluid loop

It is assumed that the central fluid loop is constructed such that all units receive fluid at the same temperature. The fluid temperature is calculated each hour by adding the temperature change, caused by the net heat gain or loss of the loop, to the past hour's loop temperature. The net heat gain to the loop (QCZ) is the sum of the gains from all units that are operating in the cooling mode. This total heat gain for each cooling zone is the sum of the zone (space) cooling load (including fan heat), plus the compressor energy consumption.

$$QCZ = \sum_{nz=1}^{nzones} [ZQC_{nz} + (EIR_{nz} * QCT_{nz})] * MULTIPLIER_{nz}, \qquad (IV.442)$$

where QCT = the rated cooling capacity of the zone unit as defined in Eq. (IV.413).

Similarly, the fluid loop heat loss (QHZ) is the sum of the losses from all units that are operating in the heating mode. This total heat loss for each heating zone is the zone (space) heating load (including fan heat) minus the compressor energy consumption.

$$QHZ = \sum_{nz=1}^{nzones} [ZQH_{nz} - (EIR_{nz} * QHT_{nz})] * MULTIPLIER_{nz}. \qquad (IV.443)$$

The resultant fluid loop temperature for the current hour is then calculated as

$$FTEMP = \langle FLUIDT \rangle_{last\ hour} + \frac{(QHZ + QCZ)}{FLUID\text{-}HEAT\text{-}CAP}. \qquad (IV.444)$$

It is further assumed that the PLANT equipment can maintain the loop temperature between the specified values for MIN-FLUID-T and MAX-FLUID-T. Thus, if the calculated fluid temperature is larger than MAX-FLUID-T, and cooling is scheduled to be on, the cooling load passed to PLANT (QC) is calculated as

$$QC = (FTEMP - MAX\text{-}FLUID\text{-}T) * FLUID\text{-}HEAT\text{-}CAP. \qquad (IV.445)$$

Similarly for heating, if the calculated fluid temperature falls below MIN-FLUID-T, and heating is scheduled to be on, the heating load passed to PLANT (QH) is calculated as

$$QH = (FTEMP - MIN\text{-}FLUID\text{-}T) * FLUID\text{-}HEAT\text{-}CAP. \qquad (IV.446)$$

Some system-level quantities are saved for reporting. These include the total system electrical energy consumption,

$$<SKW> = \sum_{nz=1}^{nzones} ZKW_{nz} * MULTIPLIER_{nz}, \qquad (IV.447)$$

total electrical input for cooling,

$$SKWQC = \sum_{nz=1}^{nzones} EIR_{nz} * QCT_{nz} * MULTIPLIER_{nz} * 0.000293 \qquad (IV.448)$$

(where 0.000293, or 1/3413, converts Btu/hr to kilowatt-hr),

total electrical input for heating,

$$SKWQH = - \sum_{nz=1}^{nzones} EIR_{nz} * QHT_{nz} * MULTIPLIER_{nz} * 0.000293, \qquad (IV.449)$$

total fan electrical energy consumption,

$$FANKW = \sum_{nz=1}^{nzones} (FH_{nz} + FC_{nz}) * MULTIPLIER_{nz} * <SUPPLY\text{-}KW_{nz}>, \text{ and} \qquad (IV.450)$$

total space latent heat gain from people and equipment,

$$QCLAT = \sum_{nz=1}^{nzones} QCLATZ_{nz} * MULTIPLIER_{nz}. \qquad (IV.451)$$

3.2.3. Packaged Terminal Air-Conditioner (subroutine PTAC)

This subroutine simulates the heat and moisture exchange in unitary packaged terminal air-conditioners (SYSTEM-TYPE = PTAC). This simulation uses the utility subroutine TEMDEV to calculate the room air temperature and the net heat extraction/addition rate. This system is usually one or more self-contained, through-the-wall package units.

Calculation Outline

For each zone attached to this system, simulate the unit in the zone.

A. Calculate the maximum cooling and heating rates.

B. Calculate the net hourly heat addition/extraction rate and the hourly room temperature (subroutine TEMDEV).

C. Check for high or low speed operation and simulate the unit

1. in the cooling mode, and
2. in the heating mode, with the source of heating being
    a. HOT-WATER, ELECTRIC, GAS-FURNACE, OIL-FURNACE, or
    b. HEAT-PUMP.

Calculation Algorithms

This SYSTEM-TYPE has no central air handling unit, but rather it has individual units in each conditioned zone. Therefore, a simulation is performed for each zone unit separately.

A. Calculate the maximum cooling and heating rates.

To calculate the load on each unit, it is necessary to first calculate the unit's capacity this hour so that subroutine TEMDEV can be used to simulate the thermostat action and the resultant heat addition/extraction rate. By calculating, for the current hour, the unit's coil entering air conditions and the resultant cooling and heating capacities, the minimum and maximum coil exit air conditions can be calculated.

To calculate the mixed air temperature (TM), it is necessary to know the fraction (PO) of outside ventilation air in the total supply air. This fraction (PO) is calculated from the value specified for certain zone- and system-level keywords

$$PO = \frac{\text{OUTSIDE-AIR-CFM}}{\text{<CFMAX>}}, \text{ if OUTSIDE-AIR-CFM has been specified.} \qquad \text{(IV.452)}$$

Otherwise,

$$PO = \text{the larger of } \frac{\text{OA-CHANGES} * \langle\text{VOLUME}\rangle}{60.0 * \langle\text{CFMAX}\rangle}$$

$$\text{and } \frac{\text{OA-CFM/PER} * \langle\text{PEOPLE}\rangle}{\langle\text{CFMAX}\rangle}\text{, rounded to the nearest 10 CFM.}$$

If no value has been specified for OUTSIDE-AIR-CFM, OA-CHANGES, or OA-CFM/PER,

PO = MIN-OUTSIDE-AIR.

However, if MIN-AIR-SCH has been specified,

PO = the hourly value referenced by MIN-AIR-SCH.

If PO has not been given a value by any of the preceeding specifications, it defaults to zero.

The air temperature entering the coil (TM) is now estimated by using PO and the past hour's room air temperature (<TNOW>)

$$TM = (PO * DBT) + [(1.0 - PO) * \langle\text{TNOW}\rangle] + \text{SUPPLY-DELTA-T.} \qquad \text{(IV.453)}$$

The total and sensible cooling capacities (QCT and QCS respectively) are calculated by using the current hour's entering air dry-bulb temperature and the wet-bulb temperature from the previous hour plus the current hour's outdoor dry-bulb temperature.

$$QCT = \langle\text{COOLCAPZ}\rangle * \text{CVAL(COOL-CAP-FT,EWB,T) and} \qquad \text{(IV.454)}$$

$$QCS = \text{the smaller of } \Big\{[\langle\text{COOLSHZ}\rangle * \text{CVAL(COOL-SH-FT,EWB,T)}] + [\text{CONS(1)} * \langle\text{CFMAX}\rangle] * (1.0 - \text{COIL-BF}) * (TM - 80.0)\Big\} \text{ and QCT} \qquad \text{(IV.455)}$$

where

COOL-CAP-FT is a correction function to the total cooling capacity to adjust for off-rated entering wet-bulb temperature (EWB) and outdoor dry-bulb temperature (T), COOL-SH-FT is a correction function to the sensible cooling capacity to adjust for off-rated entering wet-bulb temperature and outdoor dry-bulb temperature,

EWB = the larger of <PASTWBZ> and 60.0, and

T = the larger of DBT and COOL-FT-MIN.

Thus, the minimum zone supply air temperature (TCMINZ) can be calculated as

$$TCMINZ = TM - \frac{QCS * CON}{CONS(1) * <CFMAX>} \tag{IV.456}$$

$$\text{or } MIN\text{-}SUPPLY\text{-}T - \frac{THROTTLING\text{-}RANGE}{2.0} \text{, whichever is larger.}$$

CON is a cooling flag. If CON = 0, cooling is off; if CON = 1, cooling is on.

The maximum cooling rate (<ERMAX>) is then calculated as

$$<ERMAX> = CONS(1) * <CFMAX> * (<TNOW> - TCMINZ). \tag{IV.457}$$

If the zone temperature is within the deadband of the thermostat, and this unit runs continuously because of an outside air requirement (PO $\neq$ 0.0), the heat extraction rate of the mixed air is calculated as

$$ERMAXM = CONS(1) * <CFMAX> * (<TNOW> - TM). \tag{IV.458}$$

If no outside air is used (PO = 0), the unit cycles with the zone load, thus the deadband heat extraction rate (ERMAXM) is zero.

In a similar manner, the heating capacity (QHT), the maximum supply air temperature (THMAXZ), and the maximum heat addition rate (<ERMIN>) may be calculated. If the HEAT-SOURCE is <u>not</u> equal to HEAT-PUMP, the heating capacity is simply the constant unit capacity (<HEATCAPZ>). Otherwise, the subroutine must calculate the capacity of the heat pump (QHPT) and the electric resistance heater (QE), if specified.

$$QHT = <HEATCAPZ>, \text{ if } HEAT\text{-}SOURCE \neq HEAT\text{-}PUMP \tag{IV.459}$$

$$QHT = QHPT + QE, \text{ if } HEAT\text{-}SOURCE = HEAT\text{-}PUMP$$

where

$$QHPT = <HEATCAPZ> * CVAL(HEAT\text{-}CAP\text{-}FT,DBT,TM),\ \text{or} = 0.0,\ \text{if } DBT < MIN\text{-}HP\text{-}T$$

$$QE = ELEC\text{-}HEAT\text{-}CAP,\ \text{or} = 0.0,\ \text{if } DBT > MAX\text{-}ELEC\text{-}T$$

$$THMAXZ = TM - \frac{QHT * HON}{CONS(1) * <CFMAX>} \tag{IV.460}$$

HEAT-CAP-FT is a correction function to the heating capacity to adjust for off-rated outdoor dry-bulb temperature (DBT) and entering dry-bulb temperature (TM).

HON is a heating flag. If HON = 0, heating is off; if HON = 1, heating is on.

The maximum heating rate (<ERMIN>) is then calculated as

$$<ERMIN> = CONS(1) * <CFMAX> * (<TNOW> - THMAXZ). \tag{IV.461}$$

B. Calculate the hourly net heat addition/extraction rate and the hourly room temperature (subroutine TEMDEV).

The subroutine TEMDEV is called to calculate the room air temperature at the end of the current hour and the net heat extraction/addition rate during the hour (<QNOW>). The average room temperature (TAVE) is calculated by using the zone temperatures at the end of past hour (<TPAST>) and this hour (<TNOW>),

$$TAVE = \frac{<TPAST> + <TNOW>}{2}.$$

C. Check for high or low speed operation and simulate the unit.

The unit performance can now be simulated. If FAN-CONTROL = TWO-SPEED, the subroutine first determines whether the unit is operating at the high speed or the low speed. If the net load on the unit (Q) is less than zero (indicating a heating load) and the magnitude of the load is less than the capacity of the unit at the low speed, the subroutine assumes the unit is operating at the low speed. Similarly, if the net load on the unit (Q) is greater than zero (indicating a cooling load) and the magnitude is less than the cooling capacity of the unit at the lower speed, the subroutine assumes that the unit is operating at its lower speed. If the unit is operating in low speed, the values of LSR(1) through LSR(4) are set equal to the values for LOW-SPEED-RATIOS; otherwise, these values are set equal to 1.0.

The net sensible cooling/heating load on the unit is

$$Q = \langle QNOW \rangle + [CONS(1) * \langle CFMAX \rangle * (TAVE - TM)], \text{ if } PO \neq 0 \text{ or,}$$

$$Q = \langle QNOW \rangle, \text{ if } PO = 0, \qquad (IV.462)$$

and the supply air temperature (TS) leaving the unit is calculated as

$$TS = TAVE - \frac{\langle QNOW \rangle}{CONS(1) * \langle CFMAX \rangle}, \text{ if } PO \neq 0.0, \text{ but} \qquad (IV.463)$$

$$TS = TM - \frac{F}{CONS(1) * \langle CFMAX \rangle}, \text{ if } PO = 0.0,$$

where

$F = QCS$, if $Q > 0.0$ and
$F = QHT$, if $Q \leq 0.0$.

$TS = TM$, if TAVE is within the deadband of the thermostat.

If TM is equal to TS, no compressor energy is required. Also, if TM = TS and no outside ventilation air is required (PO = 0.0), no fan energy is required. Again, if TM = TS and outside ventilation air is required (PO > 0.0), the heating and cooling air flow rates (FH and FC respectively) are set to half the required air flow rate [<CFMAX> * LSR(1)].

1. The Cooling Mode

If TM is larger than TS, the unit is in the cooling mode. If outside ventilation air is required (PO > 0.0), the fans run continuously. If no outside ventilation air is required (PO = 0.0), the fans will cycle with the compressor to meet the cooling load. Thus, the cooling supply air flow rate (FC) is calculated as

$$FC = \langle CFMAX \rangle * LSR(1), \text{ if } PO > 0.0, \text{ and} \qquad (IV.464)$$

$$FC = \frac{\langle QNOW \rangle}{\langle ERMAX \rangle * LSR(4)} * \langle CFMAX \rangle * LSR(1), \text{ if } PO = 0.0.$$

The subroutine next determines if the coil is wet or dry. The contact between the cooling coil and the mixed air is characterized by the coil bypass factor (CBF). This value is assumed to be the product of the rated bypass factor (COIL-BF) and two modifier functions to adjust for off-design conditions

$$CBF = COIL\text{-}BF * CVAL(COIL\text{-}BF\text{-}FT, EWB, T) * CVAL(COIL\text{-}BF\text{-}FCFM, PLRCFM) \qquad (IV.465)$$

where

COIL-BF-FT is a correction function to the coil bypass factor to adjust for off-rated entering wet-bulb temperature (EWB) and entering dry-bulb temperature (T),

COIL-BF-FCFM is a correction function to the coil bypass factor to adjust for off-rated air flow rate caused by part load operation (PLRCFM),

EWB = the past hour's entering wet-bulb temperature and

PLRCFM = <CFMAX> / RATED-CFM.

To perform a moisture balance on the room, the subroutine needs to know the coil surface conditions of temperature (TSURF) and humidity ratio (WSURF). TSURF is calculated by using the bypass relationship,

$$TSURF = \frac{TC - (CBF * TM)}{1.0 - CBF} \qquad (IV.466)$$

where TC is the supply air temperature leaving the coil during the time the compressor is operating,

$$TC \doteq TM - \frac{QCS * LSR(4)}{CONS(1) * <CFMAX>}, \text{ or MIN-SUPPLY-T, whichever is larger.}$$

The saturation humidity ratio (WSURF) is calculated at TSURF and the atmospheric pressure (PATM). A moisture balance on the space, equating gains and losses, is expressed as

$$(FC * WCOIL) + (<CFMINF> * HUMRAT) + \Delta W = (FC * WR) + (<CFMINF> * WR) \qquad (IV.467)$$

where WCOIL = coil exit air humidity ratio,
<CFMINF> = infiltration air flow rate,
WR = room air humidity ratio, and

$\Delta W = \frac{<QL>}{CONS(2)}$, the space latent heat gain from people and equipment.

By defining $F = \frac{<CFMINF>}{FC}$ and $DW = \frac{\Delta W}{FC}$,

and rearranging Eq. (IV.467), WR becomes

$$WR = \frac{WCOIL + DW + (F * HUMRAT)}{1.0 + F} . \qquad (IV.468)$$

It is also known that the mixed air humidity ratio (WM) is

$$WM = (PO * HUMRAT) + [(1.0 - PO) * WR]. \qquad (IV.469)$$

Combining Eqs. (IV.468) and (IV.469), and assuming no moisture condensation on the cooling coil (that is, WCOIL = WM), yields

$$WM = HUMRAT + \left\{\left[\frac{(1.0 - PO)}{(F + PO)}\right] * DW\right\}. \qquad (IV.470)$$

If the amount of outside ventilation air plus infiltration air is zero, the right-hand side of the previous equation is replaced by (HUMRAT + DW). If the value of WM is less than WSURF, the coil is dry and it is necessary only to calculate the sensible cooling load (with no latent load, the sensible load is the total load).

$$ZQC = (TM - TS) * CONS(1) * FC. \qquad (IV.471)$$

If the calculated mixed air humidity ratio is greater than the coil surface humidity ratio at saturation, condensation will take place. The bypass relationship (CBF) relates coil entering and exiting humidity ratios

$$WCOIL = (CBF * WM) + [(1.0 - CBF) * WSURF]. \qquad (IV.472)$$

Combining Eqs. (IV.468), (IV.469), and (IV.472) gives

$$WR = \frac{(CBF * PO * HUMRAT) + [(1.0 - CBF) * WSURF] + DW + (F * HUMRAT)}{1.0 + F - [CBF * (1.0 - PO)]} \tag{IV.473}$$

and by reapplying Eqs. (IV.469) and (IV.472), WM and WCOIL are calculated. The sensible part of the cooling coil load is calculated as in Eq. (IV.471), with the latent cooling load (QCLATZ) as an additional load

$$QCLATZ = (WM - WCOIL) * CONS(2) * FC \tag{IV.474}$$

The total cooling load, sensible plus latent, for the zone (ZQC) is then

$$ZQC = [(TM - TS) * CONS(1) * FC] + QCLATZ. \tag{IV.475}$$

The coil entering wet-bulb temperature (EWB) is then calculated at TM, WM, and the atmospheric pressure (PATM).

It is necessary next to calculate the compressor energy input. First, the hourly cooling capacity (QCT) of the unit is recalculated so that the energy estimate is as close as possible. The electric input ratio (EIR) is assumed to be the product of the design (rated) EIR and two modifier functions, one for off-design air temperatures and the other for compressor part load effects

$$\begin{aligned} EIR = {} & COOLING\text{-}EIR * CVAL(COOL\text{-}EIR\text{-}FT,EWB,T) \\ & * CVAL(COOL\text{-}EIR\text{-}FPLR,PLRC) \end{aligned} \tag{IV.476}$$

where PLRC = ZQC/QCT.

The total electrical energy consumed in this zone (ZKW) is the sum of the LOADS electrical, the compressor electrical, and the fan electrical energy consumptions

$$ZKW = <ZKW> + (EIR * QCT * 0.000293) + (FC * <SUPPLY\text{-}KW>), \tag{IV.477}$$

where 0.000293 (or 1/3413) converts Btu/hr to kilowatt-hr.

2. The Heating Mode

If TM is less than TS, the unit is in the heating mode. Again, if outside ventilation air is required (PO > 0.0), the fans run continuously. If no outside ventilation air is required (PO = 0.0), the fans cycle with the unit to meet the heating load. Thus, the heating air flow rate (FH) is calculated as

$$FH = <CFMAX> * LSR(1), \text{ if } PO > 0.0, \text{ and} \tag{IV.478}$$

$$FH = \frac{<QNOW>}{<ERMIN> * LSR(4)} * <CFMAX> * LSR(1), \text{ if } PO = 0.0.$$

From Eq. (IV.470) the mixed air humidity ratio (WM) and the mixed air wet-bulb temperature can be calculated. The hourly zone heating load is calculated as

$$ZQH = (TM - TS) * CONS(1) * FH. \tag{IV.479}$$

If the HEAT-SOURCE is HOT-WATER or HOT-WATER/SOLAR, the total load to be passed to PLANT is calculated as

$$QH = \sum_{nz=1}^{nzones} ZQH_{nz} * MULTIPLIER_{nz}. \tag{IV.480}$$

If the HEAT-SOURCE is HOT-WATER/SOLAR, the total (system level) zone coil load (QHZP), the total air flow rate (CFMZP), and the average coil entering temperature (TZP) are calculated and saved for later use by the solar simulator in the PLANT program

$$QHZP = \sum_{nz=1}^{nzones} ZQH_{nz} * MULTIPLIER_{nz}, \tag{IV.481}$$

$$CFMZP = \sum_{nz=1}^{nzones} <CFMAX> * LSR(1) * MULTIPLIER_{nz}, \text{ and} \tag{IV.482}$$

$$TZP = \frac{\sum_{nz=1}^{nzones} TM * <CFMAX> * LSR(1) * MULTIPLIER_{nz}}{CFMZP}. \tag{IV.483}$$

If the HEAT-SOURCE is GAS-FURNACE or OIL-FURNACE, the subroutine FURNAC is called to simulate the furnace.

If the HEAT-SOURCE has been specified to be equal to HEAT-PUMP, a more complicated simulation must be performed. First, the heat pump capacity is recalculated, knowing the actual room temperature and adjusting for any defrosting. QHPT is recalculated as defined in Eq. (IV.459). The defrosting fraction of the hour (EIRM3) is defined by the user-specified performance function DEFROST-DEGRADE. There is no default function for DEFROST-DEGRADE;

$$\text{EIRM3} = \text{CVAL(DEFROST-DEGRADE,WBT,DBT), however} \qquad \text{(IV.484)}$$

$$\text{EIRM3} = 0.0, \text{ if DBT} > \text{DEFROST-T.}$$

The part of the heating load attributed to the electric resistance heater (Q) is that portion of the load above the heat pump capacity (QHPT). This is the entire heating load if the outdoor dry-bulb temperature is less than MIN-HP-T

$$\text{Q} = \text{ZQH} - [\text{QHPT} * \text{LSR}(3) * (1.0 - \text{EIRM3})]. \qquad \text{(IV.485)}$$

The heating load on the heat pump (QHP) is that portion of ZQH not met by Q, but not exceeding the heating capacity of the heat pump (QHPT)

$$\text{QHP} = \text{ZQH} - \text{Q}. \qquad \text{(IV.486)}$$

The defrost load (QD) is the defrost run fraction (EIRM3) times the available capacity

$$\text{QD} = \text{EIRM3} * \frac{\text{QHP}}{\text{QHPT}} * \text{QHPT}. \qquad \text{(IV.487)}$$

The operating electric input ratio (EIR) for this hour is the design (or rated) HEATING-EIR multiplied by three adjusting functions, one for off-design temperatures, one for off-design loading, and one for off-design CFM

$$\text{EIR} = \text{HEATING-EIR} * \text{CVAL(HEAT-EIR-FT,DBT,TM)}$$
$$* \text{CVAL(HEAT-EIR-FPLR,PLRH)} * \text{CVAL(RATED-HEIR-FCFM,PLRCFM)}$$
$$\text{(IV.488)}$$

where

$$PLRH = \frac{QHP + QD}{QHPT}$$ (assuming the defrost EIR and the space heat mode are approximately equal) and

$$PLRCFM = \frac{<CFMAX>}{RATED\text{-}CFM} .$$

The total electrical energy consumption for this zone is the sum of the electrical consumption calculated by LOADS plus the compressor energy (including defrost), the electric resistance heat, and the fan energy consumptions

$$ZKW = <ZKW> + \left\{[QHPT * EIR + (Q + QD)] * 0.000293\right\} + [FC * <SUPPLY\text{-}KW> * LSR(2)]. \tag{IV.489}$$

3.2.4. Unit Heaters and Unit Ventilators (subroutines UNITH and UNITV)

These subroutines simulate the operation of unitary heaters and unitary ventilators (SYSTEM-TYPE = UHT or UVT). These are individual units located within each zone. These units have fans and heating coils. The unit ventilator, in addition, has a moveable outside air damper that is opened in response to a space temperature above the heating set point.

Calculation Outline

For each zone attached to this system, simulate the unit.

A. Calculate the maximum cooling and heating rates.

B. Calculate the hourly room air temperature and the hourly heat extraction/addition rate (subroutine TEMDEV).

C. Calculate the load on the heating coil and save all quantities that would be needed for a solar system simulation.

Calculation Algorithms

A. Calculate the maximum cooling and heating rates.

For the unit heater, this is simple. This unit has no outside air capability and the fan cycles with the heat source to meet the heating load. Thus, at the top of the heating throttling range the unit is off, resulting in zero heat addition, and at the bottom of the range, the unit heater experiences full air flow and maximum heat addition equal to the design unit capacity plus fan heat gain.

For the unit ventilator, the simulation is slightly more complex

<ERMAX> = 0.0 (IV.490)

<ERMIN> = <HEATCAPZ> + [CONS(1) * <CFMAX> * SUPPLY-DELTA-T],

or 0.0 if the fan or heating is scheduled to be off.

The unit ventilator has an outside air damper that opens in response to a room temperature above the heating set point. The damper returns to its minimum position when the unit is in the heating mode. Additionally, when, because of NIGHT-CYCLE-CTRL, the unit has cycled on to hold a night setback temperature, the outside air damper is assumed to stay closed. This unit runs the fans continuously (when scheduled to be on) except during this night heating cycle.

The mixed air temperature needs to be calculated. To do this, it is necessary to know the minimum quantity of outside ventilation air. When in the cooling mode, the unit ventilator uses 100 per cent outside air. Thus, the minimum supply air temperature (TCMINZ) and the resultant heat extraction rate (<ERMAX>) can be calculated

$$\text{TCMINZ} = \text{DBT} + \text{SUPPLY-DELTA-T} \tag{IV.491}$$

$$\text{<ERMAX>} = \text{CONS}(1) * \text{<CFMAX>} * (\text{<TNOW>} - \text{TCMINZ}). \tag{IV.492}$$

In the heating mode, the minimum fraction (PO) of outside air in the total supply air is calculated from the value specified for certain zone- and system-level keywords

$$\text{PO} = \frac{\text{OUTSIDE-AIR-CFM}}{\text{<CFMAX>}}\text{ , if OUTSIDE-AIR-CFM has been specified.} \tag{IV.493}$$

Otherwise,

$$\text{PO} = \text{the larger of } \frac{\text{OA-CHANGES} * \text{<VOLUME>}}{60.0 * \text{<CFMAX>}}\text{ , or}$$

$$\frac{\text{OA-CFM/PER} * \text{<PEOPLE>}}{\text{<CFMAX>}}\text{, rounded to the nearest 10 cfm.}$$

If no value has been specified for OUTSIDE-AIR-CFM, OA-CHANGES, or OA-CFM/PER,

$$\text{PO} = \text{MIN-OUTSIDE-AIR}.$$

However, if MIN-AIR-SCH has been specified,

$$\text{PO} = \text{the hourly value referenced by MIN-AIR-SCH}.$$

If PO has not been given a value by any of the preceeding specifications, it defaults to zero.

If NIGHT-CYCLE-CTRL has caused the system to be turned on this hour (that is, the fan flag for NIGHT-CYCLE-CTRL, FONNGT $\neq$ 0.0), the value for PO is set to zero. Next, it is necessary to calculate the mixed air temperature (TM), the maximum supply air temperature (THMAXZ), and the resultant maximum heating rate (<ERMIN>).

$$\text{TM} = (\text{PO} * \text{DBT}) + [(1.0 - \text{PO}) * \text{<TNOW>}] + \text{SUPPLY-DELTA-T} \tag{IV.494}$$

$$THMAXZ = TM - \frac{<HEATCAPZ> * HON}{CONS(1) * <CFMAX>} \text{ or MAX-SUPPLY-T, whichever is smaller.} \quad (IV.495)$$

HON is a heating flag. If HON = 0, heating is off; if HON = 1, heating is on.

$$<ERMIN> = CONS(1) * <CFMAX> * (<TNOW> - THMAXZ) \quad (IV.496)$$

The minimum heating rate, which is also the deadband heating rate (ERMAXM) is calculated, assuming that mixed return and outside air flows into the room

$$ERMAXM = CONS(1) * <CFMAX> * (<TNOW> - TM). \quad (IV.497)$$

B. Calculate the hourly room air temperature and the hourly heat extraction/addition rate.

The subroutine TEMDEV is called to calculate the room air temperature at the end of the current hour (replaces <TNOW>) and the net heat extraction/addition rate during the hour (<QNOW>). The average room air temperature (TAVE) is calculated by using the temperatures at the end of the previous and current hours, <TPAST> and <TNOW>, that is

$$TAVE = \frac{<TPAST> + <TNOW>}{2} .$$

C. Calculate the load on the heating coil and save all quantities that would be needed for a solar system simulation.

For the unit heater or unit ventilator in the night heating cycle, the air flow rate (CFMZ), the zone heating coil load (ZQH), and the fan energy consumption (ZFANKW) are calculated as follows

$$CFMZ = \frac{<QNOW>}{<ERMIN>} * <CFMAX> \quad (IV.498)$$

$$ZQH = <QNOW> + [CONS(1) * CFMZ * SUPPLY\text{-}DELTA\text{-}T] \quad (IV.499)$$

$$ZFANKW = CFMZ * SUPPLY\text{-}KW. \quad (IV.500)$$

For a unit ventilator not in the night heating cycle, slightly more complicated expressions are used because the fans run continuously and the heating coil cycles with the heating load

$$\text{ZQH} = [\text{CONS}(1) * <\text{CFMAX}> * (\text{TM} - \text{TAVE})] + <\text{QNOW}> \tag{IV.501}$$

$$\text{CFMZ} = <\text{CFMAX}> \tag{IV.502}$$

$$\text{ZFANKW} = \text{CFMZ} * \text{SUPPLY-KW} \tag{IV.503}$$

where TM is recalculated as

$$\text{TM} = (\text{PO} * \text{DBT}) + [(1.0 - \text{PO}) * \text{TAVE}] + \text{SUPPLY-DELTA-T}.$$

If the heat source is specified as GAS-FURNACE or OIL-FURNACE, the subroutine FURNAC is called to simulate the furnace. If the HEAT-SOURCE is HOT-WATER/SOLAR (the default value), the total (system-level) zone coil load (QHZP), the total air flow rate (CFMZP), and the average coil entering air temperature are calculated and saved for later use by the solar simulator in the PLANT program,

$$\text{QHZP} = \sum_{nz=1}^{nzones} \text{ZQH}_{nz} * \text{MULTIPLIER}_{nz}, \tag{IV.504}$$

$$\text{CFMZP} = \sum_{nz=1}^{nzones} \text{CFMZ}_{nz} * \text{MULTIPLIER}_{nz}, \text{ and} \tag{IV.505}$$

$$\text{TZP} = \frac{\sum_{nz=1}^{nzones} \text{TM}_{nz} * \text{CFMZ}_{nz} * \text{MULTIPLIER}_{nz}}{\text{CFMZP}}. \tag{IV.506}$$

The total fan electrical energy consumption (FANKW), the total electrical energy consumption (<SKW>), and the total zone coil heating load (QHZ) are also calculated at the system level,

$$\text{FANKW} = \sum_{nz=1}^{nzones} \text{FANKW}_{nz} * \text{MULTIPLIER}_{nz}, \tag{IV.507}$$

$$\langle SKW\rangle = \sum_{nz=1}^{nzones} (ZKW_{nz} + ZFANKW_{nz}) * MULTIPLIER_{nz}, \text{ and} \tag{IV.508}$$

$$QHZ = \sum_{nz=1}^{nzones} ZQH_{nz} * MULTIPLIER_{nz}. \tag{IV.509}$$

3.2.5. Panel Heating (subroutine PANEL)

This subroutine is intended to simulate panel heating systems (SYSTEM-TYPE = FPH). Cooling and outside ventilation air are not allowed in this subroutine. Thus, it is suggested that if panel heating is required, in addition to cooling and/or ventilation, one of the other SYSTEM-TYPEs be used with baseboard heaters input to simulate the heating panels. This subroutine is very rudimentary and, thus, not suggested for use.

Calculation Outline

For each zone attached to the system, calculate the panel heating energy.

A. Set the heating limits and call subroutine TEMDEV to calculate the hourly room air temperature and the hourly net heating.

B. Calculate the panel energy and sum the electrical energy.

Calculation Algorithms.

For each zone attached to this system, calculate the heating energy input to the zone panel.

A. The maximum and minimum heat addition rates (<ERMIN> and <ERMAX> respectively) are set to the design heating maximum, as passed by LOADS or input by the user, and zero respectively

<ERMIN> = <ERMIND> (IV.510)

<ERMAX> = 0.0. (IV.511)

TEMDEV is then called to calculate the room air temperature at the end of the current hour and the net zone heat addition rate for the hour.

B. The heating energy input to the panel is calculated as the zone net heating (<QNOW>), adjusted for the panel losses

ZQH = <QNOW> * (1.0 + PANEL-LOSS-RATIO). (IV.512)

The total heating load and zone electrical energy consumption (QH and <SKW>) are calculated at the system level

$$QH = \sum_{nz=1}^{nzones} ZQH_{nz} * MULTIPLIER_{nz} \text{ and} \qquad (IV.513)$$

$$\langle SKW \rangle = \sum_{nz=1}^{nzones} ZKW_{nz} * MULTIPLIER_{nz}. \qquad (IV.514)$$

Note that no ventilation load is calculated by this system. Any outside ventilation air must be accounted for by specifying infiltration air in the LOADS program.

3.3 Special System - The Summation System (subroutine SUM)

This subroutine does not simulate a HVAC system. SUM is intended to be a method of summing the zone loads, as calculated by the LOADS program, while also taking into account the zone thermostat settings and the availability of heating and cooling. Thus, no outside ventilation air or system efficiencies are accounted for. This subroutine is useful for calculating the base envelope load that drives the system simulation. Thus, the output from this subroutine can be used as a basis for comparing the performance, and especially efficiencies, of the different SYSTEM-TYPEs.

Calculation Outline

For each zone attached to the system, sum the loads.

A. Determine the maximum cooling and heating rates.

B. Calculate the hourly room air temperature and the hourly heat extraction/addition rate (subroutine TEMDEV).

C. Sum the heating and cooling loads.

Calculation Algorithms

For all the zones attached to this system, the subroutine sums the net heat extraction or addition required.

A. First, the maximum cooling and heating rates are determined. These are simply the constant values either (1) passed from LOADS as the peak requirements or (2) the values specified by the user. These values are found on the report SV-A. These values are set to zero if the appropriate HEATING-SCHEDULE or COOLING-SCHEDULE has a zero value for the current hour.

B. The subroutine TEMDEV is called to calculate the room air temperature at the end of the current hour (<TNOW>) and the net heat extraction/addition rate (<QNOW>) that would result in this temperature.

C. The total (system-level) heating and cooling loads (QH and QC respectively) are calculated as the sum of individual zone heating and cooling loads (ZQH and ZQC),

$$QH = \sum_{nz=1}^{nzones} ZQH_{nz} * MULTIPLIER_{nz} \text{ and} \qquad (IV.515)$$

$$QC = \sum_{nz=1}^{nzones} ZQC_{nz} * MULTIPLIER_{nz}, \qquad (IV.516)$$

where ZQH = <QNOW>, if <QNOW> < 0.0 -- if <QNOW> > 0.0, ZQH = 0, and
ZQC = <QNOW>, if <QNOW> > 0.0 -- if <QNOW> < 0.0, ZQC = 0.

The total (system-level) electrical consumption (<SKW>), the space latent heat gain from people and equipment (QLSUM), and the infiltration air flow rate (CINF) are also calculated,

$$\langle SKW \rangle = \sum_{nz=1}^{nzones} \langle ZKW \rangle_{nz} * MULTIPLIER_{nz}, \tag{IV.517}$$

$$QLSUM = \sum_{nz=1}^{nzones} \langle QL \rangle_{nz} * MULTIPLIER_{nz}, \text{ and} \tag{IV.518}$$

$$CINF = \sum_{nz=1}^{nzones} \langle CFMINF \rangle_{nz} * MULTIPLIER_{nz}. \tag{IV.519}$$

This subroutine does not calculate the latent part of the cooling load from infiltration air. The sensible part of the infiltration load, however, is included in the cooling and heating load. Because there is no ventilation in the system, there is no sensible or latent calculation for ventilation air.

4. SIMULATION SUPPORT ROUTINES

4.1. Interface Between LOADS and SYSTEMS (subroutine TEMDEV)

The routine TEMDEV calculates the zone air temperature and the heat extraction/addition rate, by using the room air temperature weighting factors and constant temperature loads, which are passed from the LOADS program. This SYSTEMS routine corrects or modifies the loads, which are calculated by the LOADS simulator, to account for effects such as thermostat schedules, heating and cooling availability, and equipment capacities.

Calculation outline

1. Calculate a correction term for interzone heat transfer.
2. Execute procedures for zones that have no plenum attachments possible and for zones with outdoor reset baseboard heaters.
3. Correct the heat extraction/addition maximum and minimum rates for temperature change during the hour.
4. Calculate the zone temperature and the heat extraction/addition rates.
5. Calculate the contribution to the heat addition from thermostatic baseboard heaters.
6. Update the history of temperature and heat extraction/addition rates.
7. Perform the calculations for unconditioned zones and plenum zones.

Calculation algorithms

Step 1. Calculation of a Correction Term for Interzone Heat Transfer

The LOADS program calculates the transfer of energy between two contiguous zones by using a $U * A * (T_1 - T_2)$ equation. In this equation, $U * A$ is actually the sum of all $U * A$ values (one for each internal wall between the two zones). U is the U-value specified for each wall and A is the area of that wall. The $(T_1 - T_2)$ term is calculated by using the LOADS calculation temperatures of the two zones (specified with the TEMPERATURE keyword in the SPACE-CONDITIONS instruction). Because none of these values (U, A, T_1, and T_2) vary as a function of time (in LOADS), this value is a constant as far as the LOADS program is concerned. SYSTEMS, however, cannot treat this quantity as a constant because the air temperature of the zones in the building are allowed to change as a function of time. Thus, SYSTEMS must calculate the correction, which will compensate for the zones not operating at their LOADS calculation temperature.

If the user starts with the weighting-factor equation that relates the room air temperature (and its history) to the heat extraction/addition rates (and its history),

$$
\begin{aligned}
(\mathrm{HENOW}-\langle QS\rangle) + [\langle P1\rangle * (\langle QNOW\rangle - \langle QSPAST\rangle)] + [\langle P2\rangle * (\langle QPAST\rangle - \langle QSPAST2\rangle)] \\
= [G0 * (\langle TLOADS\rangle - \mathrm{TRY})] + [G1 * (\langle TLOADS\rangle - \langle TNOW\rangle)] \\
+ [G2 * (\langle TLOADS\rangle - \langle TPAST\rangle)] + [G3 * (\langle TLOADS\rangle - \langle TPAST2\rangle)]
\end{aligned}
\tag{IV.520}
$$

where,

<P1>, <P2> are room air weighting factors from the LOADS simulator,

G0, G1, G2, and G3 are room air weighting factors (defined later in this section),

<QS>, <QSPAST>, and <QSPAST2> are constant temperature sensible loads calculated by the LOADS simulator,

HENOW, <QNOW>, <QPAST> are the current and past two hours' history of zone heat extraction/addition rates,

TLOADS is the zone temperature specified in the LOADS simulator, and

$$
\left.\begin{array}{l} \mathrm{TRY} \\ \langle TNOW\rangle \\ \langle TPAST\rangle \\ \langle TPAST2\rangle \end{array}\right\}
$$
are the current and past three hours' history of zone temperature.

The terms can be rearranged to form the following equation

$$
\mathrm{HENOW} = F - (G0 * \mathrm{TRY}) \tag{IV.521}
$$

where,

$$
\begin{aligned}
F = {} & [\langle TLOADS\rangle * \mathrm{SIGMAG}] + \langle QS\rangle + [\langle P1\rangle * (\langle QSPAST\rangle - \langle QNOW\rangle)] \\
& + [\langle P2\rangle * (\langle QSPAST2\rangle - \langle QPAST\rangle)] - (G1 * \langle TNOW\rangle) - (G2 * \langle TPAST\rangle) \\
& - (G3 * \langle TPAST2\rangle), \text{ and}
\end{aligned}
$$

$$
\mathrm{SIGMAG} = G0 + G1 + G2 + G3.
$$

Additionally, if it is assumed that a linear relationship exists between thermostat action, within a control-band (THROTTLING-RANGE), and the zone temperature,

$$\mathrm{HENOW} = W + (S * \mathrm{TRY}) \tag{IV.522}$$

where,

S is the slope of the line, and
W is the intercept of the line.

Combining Eqs. (IV.521) and (IV.522) and then solving first for HENOW, gives Eq. (IV.523) rearranged.

$$\mathrm{HENOW} = \frac{(\mathrm{G0} * W) + (F * S)}{S + \mathrm{G0}} \; . \tag{IV.523}$$

Then, substituting this back into Eq. (IV.521) gives

$$\mathrm{TRY} = \frac{F - \mathrm{HENOW}}{\mathrm{G0}} \; . \tag{IV.524}$$

These are the basic relationships, outlined in the weighting factors section of this manual (Chap. II) for use in obtaining the zone air temperature and the heat extraction/addition rates, when the equipment capacity and thermostat action characteristics are known.

Now, looking more closely at the terms G0, G1, G2, and G3, which are defined as,

$$\mathrm{G0} = [\langle \mathrm{G0}\rangle * \langle \mathrm{AREA}\rangle] + (\langle \mathrm{CONDUCHR}\rangle + \mathrm{CONS}(1) * \langle \mathrm{CFMINF}\rangle),$$

$$\mathrm{G1} = \langle \mathrm{G1}\rangle * \langle \mathrm{AREA}\rangle + [\langle \mathrm{P1}\rangle * (\langle \mathrm{CONDUCHRPAST}\rangle + \mathrm{CONS}(1) * \langle \mathrm{VIPAST}\rangle)],$$

$$\mathrm{G2} = \langle \mathrm{G2}\rangle * \langle \mathrm{AREA}\rangle + [\langle \mathrm{P2}\rangle * (\langle \mathrm{CONDUCHRPAST2}\rangle + \mathrm{CONS}(1) * \langle \mathrm{VIPAST2}\rangle)], \text{ and}$$

$$\mathrm{G3} = \langle \mathrm{G3}\rangle * \langle \mathrm{AREA}\rangle,$$

where

<G0>, <G1>, <G2>, and <G3> are normalized room air temperature weighting factors from the LOADS simulator,

<AREA> is the zone floor area,

<CONDUCHR>, <CONDUCHRPAST>, and <CONDUCHRPAST2> are the sum of external and internal conductance for the present hour and the past two hours,

CONS(1) is a conversion factor, cfm to Btu/hr-°F for moist air,

CFMINF is the current hour's outdoor air infiltration rate from the LOADS simulator, and

<VIPAST> and <VIPAST2> are the last two hours' infiltration.

Now, let the conductance terms in the G0, G1, and G2 terms be composed of both internal and external components.

$$\langle CONDUCHR \rangle = K_{ext} + \left[\sum_{n=1}^{\langle nattch \rangle} k_n \right] \tag{IV.525}$$

where

K_{ext} is the summed conductances of the external surfaces,

k_n is the conductance of the nth internal surface separating one zone from the rest, and

NATTCH is the total number of internal surfaces in the zone.

Using similar expressions from <CONDUCHRPAST> and <CONDUCHRPAST2>, and knowing that the sensible load from the LOADS simulator already contains the correction for different constant calculation temperatures, a new term is obtained for the right-hand side of Eq. (IV.521)

$$HENOW = F + \left[\sum_{i=0}^{2} P_i \sum_{j=1}^{\langle nattch \rangle} K_j \left(T_{j,t-i} - T_{j,L} \right) \right] - (G0 * TRY), \tag{IV.526}$$

where

P_0, P_1, and P_2 are 1.0, <P1>, and <P2> respectively,

$T_{j,t-i}$ is the temperature of the jth attached space for t-i hours past, and

$T_{j,L}$ is the constant LOADS calculation temperature of the jth attached space.

Using Eq. (IV.526) to get an analogous expression for Eqs. (IV.523) and (IV.524) would require solving all zones simultaneously. To avoid this, substitute $T_{k,t-i-1}$ for $T_{k,t-i}$ in Eq. (IV.526). This simplification assumes that the change in slope of the temperature of all zones is not changing greatly from hour to hour. Thus, the correction for the internal heat transfer is

$$\mathrm{CORINT} = X + (\langle P1 \rangle * Y) + (\langle P2 \rangle * Z), \qquad \text{(IV.527)}$$

where

CORINT is the correction in the SYSTEMS simulation for the contribution to the zone load from adjacent zones,

$$X = \sum_{\mathrm{NATTSP}=1}^{\langle \mathrm{NATTCH} \rangle} \mathrm{AA}(\mathrm{I1} + 1)[\mathrm{TEMPS}(1,\mathrm{NATTSP},\mathrm{NP}) - \mathrm{TEMPSL}(\mathrm{NATTSP})],$$

$$Y = \sum_{\mathrm{NATTSP}=1}^{\langle \mathrm{NATTCH} \rangle} \mathrm{AA}(\mathrm{I1} + 1)[\mathrm{TEMPS}(2,\mathrm{NATTSP},\mathrm{NP}) - \mathrm{TEMPSL}(\mathrm{NATTSP})], \text{ and}$$

$$Z = \sum_{\mathrm{NATTSP}=1}^{\langle \mathrm{NATTCH} \rangle} \mathrm{AA}(\mathrm{I1} + 1)[\mathrm{TEMPS}(3,\mathrm{NATTSP},\mathrm{NP}) - \mathrm{TEMPSL}(\mathrm{NATTSP})],$$

where

AA(I1 + 1) is the sum of the U*A values for all walls separating the zone being calculated and NATTSP attached space,

TEMPS(i,NATTSP,NP) is the temperature in the ith past hour of the NATTSPth attached space in the PLANT-ASSIGNMENT named NP, and

TEMPSL(NATTSP) is the LOADS calculation temperature of the NATTSPth attached space.

<u>Step 2. Procedure for Zones That Have No Plenum Attachments Possible and for Zones with Outdoor Reset Baseboard Heaters</u>

Some SYSTEM-TYPEs (SUM, FPH, TFPC, FPFC, HP, and PTAC) cannot have ZONE-TYPE = PLENUM. Also, some systems may have outdoor reset baseboard heaters. Both of these situations require modifications to Eq. (IV.520).

For SYSTEM-TYPEs that do not allow plenums, the user should always specify LIGHT-TO-SPACE = 100. If the user specifies any value less than 100, the program will add the plenum heat gain from this space <QPNOW> (or, <QP> as calculated by the LOADS simulator and passed to the SYSTEMS simulator) back into the sensible load, <QS>, in Eq. (IV.520). It is necessary to save a <QP> history, that is, <QPPAST> and <QPPAST2>, for two past hours to modify <QSPAST> and <QSPAST2> in Eq. (IV.520).

When the SYSTEM contains outdoor reset baseboard heaters, the heat output from the baseboards of this zone is calculated as

QHBZ = BON * <BASEBOARD-RATING>,

where

$$\mathrm{BON} = \mathrm{SH} + \left[\frac{\mathrm{SL} - \mathrm{SH}}{\mathrm{RH} - \mathrm{RL}}\right] * (\mathrm{DBT} - \mathrm{RL}),$$

and where

SH = SUPPLY-HI, as specified by the user,

SL = SUPPLY-LO, as specified by the user,

RH = OUTSIDE-HI, as specified by the user,

RL = OUTSIDE-LO, as specified by the user, and

DBT = outdoor dry-bulb temperature.

Note that BON is constrained between SL and SH as well.

BON, along with its history values <QBPAST> and <QBPAST2>, are treated as another extraction term and are added to <QNOW>, and its history values <QPAST> and <QPAST2>.

The combination of these two effects, that is, no plenums (with LIGHT-TO-SPACE < 100) and outdoor reset baseboard heaters, produces a new expression for the value of F [in Eq. (IV.521)],

F = (<TLOADS> * SIGMAG) + (<QS> + <QPNOW> - QHBZ) + [<P1> * (<QSPAST>

+ <QPAST> - <QNOW> - <QBPAST>)] - (G1 * <TNOW>) + [<P2> * (<QSPAST2>

+ <QPAST2> - <QPAST> - <QBPAST2>] - (G2 * <TPAST>) - (G3 * <TPAST2>).

(IV.528)

Step 3. Correct the Heat Extraction/Addition Maximum and Minimum Rates for Temperature Change During the Hour

It is now necessary to modify the maximum and minimum heat extraction and addition rates calculated for this zone by the SYSTEM-TYPE routine. This modification is made to correct these rates [which are used to determine the slope and intercept in Eq. (IV.522)] for the change of zone temperature during this time step. This correction is most important during warmup or cooldown periods following a night thermostat setup or setback.

For this correction calculation it will be assumed that the temperature profile of the space during the hour is approximated by a straight line between the starting temperature and ending temperature for the hour. Thus, HENOW, as an average for the hour, can be expressed as

$$\text{HENOW} = <\text{ERMAX}> - [\text{CONS}(1) * <\text{CFMAX}>] * 0.5\,(<\text{TNOW}> - \text{TEND}), \qquad \text{(IV.529)}$$

where

<ERMAX> is the maximum heat extraction rate for the zone temperature at the beginning of the hour <TNOW>,

<CFMAX> is the maximum supply air flow rate to the zone, and

TEND is the zone temperature at the end of the hour.

From Eq. (IV.524) it can also be seen that

$$\text{TEND} = \frac{(\text{F} - \text{HENOW})}{\text{GO}} . \qquad \text{(IV.530)}$$

Solving Eqs. (IV.529) and (IV.530) together for TEND gives

$$\text{TEND} = \frac{(\text{F} - <\text{ERMAX}> + \text{Y})}{(\text{GO} + \text{X})} . \qquad \text{(IV.531)}$$

where

$\text{X} = \text{CONS}(1) * <\text{CFMAX}> * 0.5$, and

$\text{Y} = \text{X} * <\text{TNOW}>$.

This would give a value of TEND for the zone receiving the maximum extraction rate for the full hour. Because this may not be the case, because of thermostat action, an analogous equation to Eq. (IV.531) for the case of the minimum extraction rate (ERMAXM) for the hour would be

$$\mathrm{TEND} = \frac{[\mathrm{F} - \mathrm{ERMAXM} + (\mathrm{Z} * \langle \mathrm{TNOW} \rangle)]}{(\mathrm{GO} + \mathrm{Z})}, \tag{IV.532}$$

where

$$\mathrm{Z} = \mathrm{X} * \langle \mathrm{MINCFMR} \rangle$$

and MINCFMR is the minimum supply air flow rate, expressed as a fraction of the design air flow rate.

If the value of TEND produced by Eq. (IV.531) is below the cooling THROTTLING-RANGE [that is, the thermostat set point for cooling (TCZ) minus one-half the THROTTLING-RANGE (THR)], the smaller of the value produced by Eq. (IV.532) or TCZ-THR is used. Then the maximum heat extraction rate can be recalculated as

$$\langle \mathrm{ERMAX} \rangle = \langle \mathrm{ERMAX} \rangle_{\mathrm{old}} - \mathrm{X}(\langle \mathrm{TNOW} \rangle - \mathrm{TEND}) \tag{IV.533}$$

and if ERMAXM is not zero, recalculate

$$\mathrm{ERMAXM} = \mathrm{ERMAXM}_{\mathrm{old}} - \mathrm{Z}(\langle \mathrm{TNOW} \rangle - \mathrm{TEND}) \tag{IV.534}$$

and

$$\mathrm{ERMINM} = \mathrm{ERMAXM},$$

where ERMINM is the minimum heating addition rate.

Similarly, for the maximum heat addition rate (ERMIN)

$$\mathrm{TEND} = \frac{(\mathrm{F} - \langle \mathrm{ERMIN} \rangle + \mathrm{Y})}{(\mathrm{GO} + \mathrm{X})}, \tag{IV.535}$$

where

$$\mathrm{X} = [\mathrm{CONS}(1) * \langle \mathrm{CFMAXH} \rangle] * 0.5, \text{ and}$$

$$\mathrm{Y} = \mathrm{X} * \langle \mathrm{TNOW} \rangle.$$

<CFMAXH> is the maximum air flow rate for heat addition.

The minimum heat addition rate is

$$\text{TEND} = \frac{(\text{F} - \text{ERMINM} + \text{Z} * <\text{TNOW}>)}{(\text{GO} + \text{Z})}, \tag{IV.536}$$

where

$$\text{Z} = [\text{CONS}(1) * <\text{CFMAX}> * <\text{MINCFMR}>] * 0.5$$

are calculated. If the value for TEND from Eq. (IV.535) is above the heating THROTTLING-RANGE [that is, the thermostat set point for heating (THZ) plus one-half the THROTTLING-RANGE (THR)], the maximum of the value from Eq. (IV.536) or THZ + THR is used. Then the minimum heat extraction rate can be recalculated as

$$<\text{ERMIN}> = <\text{ERMIN}>_{\text{old}} - \text{X}(<\text{TNOW}> - \text{TEND}). \tag{IV.537}$$

Step 4. Calculate the Zone Temperature and Heat Extraction/Addition Rates

It is now possible to calculate the zone temperature and heat extraction/addition rates by applying Eqs. (IV.523) and (IV.524). First, it is necessary to find where the zone temperature would be at the end of the hour if the minimum heat extraction rate is applied. This temperature, TRY, will be

(1) within or below the value referenced by the HEAT-TEMP-SCH for the heating THROTTLING-RANGE (below THZ + THR),

(2) within a dead band between the heating THROTTLING-RANGE and the cooling THROTTLING-RANGE, or

(3) within or above the value referenced by the COOL-TEMP-SCH for the cooling THROTTLING-RANGE (above TCZ - THR).

This test on TRY temperature is calculated, [using Eq. (IV.524)], as

$$\text{TRY} = \frac{(\text{F} - \text{ERMAXM})}{\text{GO}}. \tag{IV.538}$$

If TRY falls within the dead band, the zone temperature <TNOW> will be set equal to TRY and the heat extraction/addition rate <QNOW> will be ERMAXM. If the TRY values fall within either the heating or cooling THROTTLING-RANGEs, the zone heat extraction/addition rate (HENOW) can be calculated by using Eq.

(IV.524) and solving for W and S of Eq. (IV.522) for the top and bottom points of the THROTTLING-RANGE,

$$S = \frac{ERMAX - ERMIN}{\text{<THROTTLING-RANGE>}} \tag{IV.539}$$

and

$$W = \frac{ERMAX + ERMIN}{2.0} - (S * \text{<TSET>}), \tag{IV.540}$$

where, for TRY $\geq$ TCZ - THR,

ERMAX = <ERMAX> from Eq. (IV.533),
ERMIN = ERMAXM from Eq. (IV.534), and
<TSET> = value referenced by COOL-TEMP-SCH,

and for TRY $\leq$ THZ + THR,

ERMIN = <ERMIN> from Eq. (IV.537) + <BASEBOARD-RATING>,
ERMAX = ERMINM from Eq. (IV.534), and
<TSET> = value referenced by HEAT-TEMP-SCH.

Because Eq. (IV.523) can produce a HENOW that is outside the limits of heat extraction/addition (ERMAX, ERMIN), it is necessary to constrain HENOW within limits. Thus, QOVER is set to the amount by which HENOW exceeds the limit.

Step 5. Calculate the Contribution to the Heat Addition for Thermostatic Baseboard Heaters

The value of <QNOW> is used in the HVAC air system calculation to determine the supply air quantity, the reheat energy, or other system requirements. If the user has specified BASEBOARD-CTRL = THERMOSTATIC, the baseboard heaters will sequence into action before any other heating device. Thus, the value of <QNOW> is reduced by the amount of heat provided by the baseboard heaters (QHBZ). However, <QHBZ> will not exceed the baseboard capacity.

QHBZ = larger of <QNOW> or <BASEBOARD-RATING>,

and

$$\text{<QNOW>} = \text{<QNOW>}_{old} - QHBZ.$$

Step 6. Update the History of the Zone Temperature and the Heat Extraction/ Addition Rate

Before returning to the HVAC air system calculation for the zone, it is necessary to update the history for <QNOW>, <TNOW>, and QHBZ. It is also necessary to save the current zone temperature (<TNOW>) in position 4 of the TEMPS array for use next hour in the internal transfer correction term.

Step 7. Calculations for Unconditioned Zones and Plenum Zones

For zones that are either UNCONDITIONED or a PLENUM, it is necessary to modify the calculation of zone temperature, air quantities, and heat extraction/addition rates. UNCONDITIONED zones have no active heating or cooling. PLENUM zones are zones that have an induced return air, which enters the PLENUM zone at the average temperature of the zone being served.

In an UNCONDITIONED zone, HENOW is set to zero and Eq. (IV.524) becomes

$$TRY = F/GO. \tag{IV.541}$$

This value is then used as the zone temperature.

In PLENUM zones, air is induced at the average zone temperature. Because more than one return air plenum may exist, the total amount of return air is apportioned to each plenum, based on the ratio of zone floor areas to total PLENUM area for each plenum. The amount of air moving through each PLENUM zone (ACFM) is calculated as

$$ACFM = \frac{RCFM * \langle AREA \rangle}{\langle PLENMULT \rangle} ,$$

where

RCFM = total return air quantity,

<AREA> = the floor area of the PLENUM zone, and

$$\langle PLENMULT \rangle = \sum_{n=1}^{\text{number of plenums}} \langle AREA \rangle * \langle MULTIPLIER \rangle.$$

For a return air plenum, the heat exchange between the return air and the plenum is calculated as

$$\mathrm{HENOW} = [\mathrm{CONS}(1) * \mathrm{ACFM} * (<\mathrm{TNOW}>-\mathrm{TR})] - [\mathrm{CONS}(1) * \mathrm{ACFM} * 0.5 * (<\mathrm{TNOW}>-\mathrm{TRY})] \tag{IV.542}$$

where TR is the return air temperature.

If this is solved with substitution of Eq. (IV.524) for TRY

$$\mathrm{HENOW} = \frac{X}{\mathrm{GO} + X} * [F + \mathrm{GO}\ (<\mathrm{TNOW}> - 2.0 * \mathrm{TR})], \tag{IV.543}$$

where

$$X = \mathrm{CONS}(1) * \mathrm{ACFM} * 0.5.$$

The zone temperature is then calculated using Eq. (IV.524) with the value from Eq. (IV.543) and the temperature and extraction histories are updated in the normal way.

4.2. Furnace Simulation (subroutine FURNAC)

The routine FURNAC is called to simulate a gas-fired or oil-fired furnace. The subroutine accepts, as input, the furnace load (QHF), the furnace capacity (CAP), the fuel type (IFUEL), and the number of similar furnaces with the given load (QMULT).

Calculation outline

1. Adjust the furnace load for losses during the off part of the furnace cycle.

2. Calculate the fuel input to the furnace and calculate the auxiliary energy input to the furnace.

Calculation algorithms

Step 1. Adjust the Furnace Load for Losses During the Off Part of the Furnace Cycle

During the off cycle of the fan, as the furnace cools, a draft is induced through the flue. This induced draft will cause an infiltration loss to makeup the air flowing up through the flue. This will only be of importance when the makeup air flows from the conditioned space, thus inducing an infiltration makeup load on the space. Also, this will only be important when the furnace runs part of the hour, but not for the full hour. The user may enter a curve, as a function of outdoor dry-bulb temperature, which expresses the fraction of the unused furnace capacity (CAP - QHF) associated with the induced draft load. There is no default curve for FURNACE-OFF-LOSS; the user must input it using the CURVE-FIT instruction (see BDL) or the effect will be lost. Thus,

$$QHLOSS = (CAP - QHF) * CVAL(<FURNACE\text{-}OFF\text{-}LOSS>,DBT), \tag{IV.544}$$

where CVAL (<FURNACE-OFF-LOSS>,DBT) is the value of the function <FURNACE-OFF-LOSS>, evaluated at DBT, the outdoor dry-bulb temperature.

Step 2. Calculate the Fuel Input to the Furnace and Calculate the Auxiliary Energy Input to the Furnace

To calculate the fuel input to the furnace, the part-load ratio of the furnace is calculated first as

$$PLRF = (QHF + QHLOSS)/CAP. \tag{IV.545}$$

This value is used, along with the design capacity heat input ratio and the part-load ratio curve, to calculate the fuel input

$$FFUEL = CAP * FURNACE\text{-}HIR * CVAL(FURNACE\text{-}HIR\text{-}FPLR, PLRF), \quad (IV.546)$$

where

FURNACE-HIR = the heat input ratio of the furnace at full load and
FURNACE-HIR-FPLR = the curve that describes the deviation of the heat input ratio from that at full load, as a function of part-load ratio.

Next, the total gas or oil used this hour is incremented by the amount used by this furnace. For IFUEL = 2, indicating a gas-fired furnace,

$$SGAS = SGAS_{old} - FFUEL*QMULT. \quad (IV.547)$$

(FFUEL is negative, however, SGAS is positive).

For IFUEL = 3, indicating an oil-fired furnace,

$$SOIL = SOIL_{old} - FFUEL*QMULT \quad (IV.548)$$

and electrical energy for the system (<SKW>), as well as for electric heating (SKWQH) are incremented for any auxiliary pumps and spark ignition system using Eq. (IV.549)

$$FURNACE\text{-}AUX * PLRF * QMULT * 0.000293, \quad (IV.549)$$

where 0.000293 (or 1/3413) converts Btu/hr to kilowatt-hr and

FURNACE-AUX = the Btus of auxiliary heat input at full load.

If the furnace load or capacity is less than 10 Btu/hr, the furnace does not run. If, however, the HEAT-SOURCE = GAS-FURNACE and the furnace load or capacity is less than 10 Btu/hr, the total system gas is incremented by <FURNACE-AUX> * QMULT, to account for the pilot light.

4.3. Control of Hot and Cold Duct Supply Temperatures (subroutine DKTEMP)

The routine DKTEMP is called to calculate the hot and/or cold duct supply air temperatures (TH and TC respectively). TH and TC are the temperatures of the air leaving the heating coil and cooling coil, respectively. This subroutine will also calculate the maximum and minimum supply air temperatures (THMAX and TCMIN respectively). This routine uses the information about coil capacities, controller set points, and method of operation, along with the zone temperatures, to predict the return and mixed air conditions, and thus, to predict the supply air limits. The ability of this routine to accurately predict the return and mixed air conditions is very important because the resultant supply air temperatures will be used to calculate each zone's heating and cooling capacities. This routine becomes especially important when heating and/or cooling are scheduled to be off, because the temperatures calculated here will entirely govern the availability of heating and/or cooling during those hours.

This routine is called before the "zone loop" calculations are performed for each system, because the supply air temperatures must be known before any zone temperatures and heat extraction/addition rates can be calculated. However, because the supply air temperatures are dependent on zone and outside conditions, the exact solution to the problem would require a simultaneous solution of all zone and supply air temperatures. This is not practical in a program of this type, and instead a semi-iterative approach will be used. Thus, DKTEMP, using the previous hour's condition, predicts the current hour's condition. Later, in the "zone loop" of the system simulation, a second pass is made and a much more exact calculation is done.

Calculation Outline

1. Estimate the return air temperature.
2. Estimate the mixed air temperature limits.
3. Calculate the minimum supply air temperature.
4. Calculate the cold duct supply air temperature
   (a) CONSTANT or SCHEDULED,
   (b) WARMEST, or
   (c) RESET.
5. Calculate the maximum supply air temperature.
6. Calculate the hot duct supply air temperature
   (a) CONSTANT or SCHEDULED,
   (b) COLDEST, or
   (c) RESET.

Calculation Algorithms

Step 1. Estimate the Return Air Temperature

The first step to calculating the mixed air condition is to calculate the return air temperature. To do this, it is necessary to know the air quantities and temperatures for each zone. In a constant air volume system, the air quantity presents no problem. In a variable air volume system, this will depend upon the supply air and zone temperatures. Obviously, because the supply air and zone temperatures are interdependent, an exact solution for these values would require solving all zone and supply air temperatures simultanously. Instead of using that approach, the zone temperature from the end of the previous hour and the fraction of total supply air for the system from the previous hour are used.

If the fans were running the previous hour, the fraction of the design CFM (CFMDIV) is calculated as

$$\text{CFMDIV} = \langle\text{PASTCFM}\rangle \;/\; (\text{SUPPLY-CFM} \;/\; \langle\text{CFMRATIO}\rangle), \tag{IV.550}$$

where

<PASTCFM> = the total system supply air CFM from the previous hour of fan operation,

SUPPLY-CFM = the rated capacity for supply air fan, and

$$\langle\text{CFMRATIO}\rangle = \frac{\text{SUPPLY-CFM}}{\sum\limits_{nz=1}^{nzone} \langle\text{CFMAX}\rangle} \ .$$

nzone is the total number of zones in the system and <CFMAX> is the maximum supply air flow rate for each zone. If the fans were off during the previous hour, it will be assumed that the supply air quantity will be that required for maximum heating or cooling. Thus,

$$\text{CFMDIV} = \langle\text{CFMRATIO}\rangle \tag{IV.551}$$

or

$$\text{CFMDIV} = \frac{\langle\text{CFMH}\rangle}{(\text{SUPPLY-CFM} \;/\; \langle\text{CFMRATIO}\rangle)} \ ,$$

if <PASTCFM> is approximately <CFMH>, where

$$\langle\text{CFMH}\rangle = \sum_{nz=1}^{nzones} \langle\text{CFMAXH}\rangle, \text{ and}$$

<CFMAXH> = the maximum air flow to a zone in the heating mode.

In both these cases (fans running the previous hour and fans off the previous hour), the value of CFMDIV is not allowed to go above 1.0.

Now, the weighted average return air temperature, total supply and exhaust air quantities, and light-to-plenum heat gain are calculated. The return air temperature (TR) entering the plenum is calculated as

$$TR = \frac{\sum_{nz=1}^{nzone} \text{<TNOW>} * (\text{<CFMAX>} * \text{CFMDIV} - \text{EXHAUST-CFM}) * \text{MULTIPLIER}}{\text{CFM} - \text{ECFM}}$$

$$+ \frac{QP}{\text{CONS(1)} * (\text{CFM} - \text{ECFM})}, \qquad \text{(IV.552)}$$

where

<TNOW> is the zone temperature for the current hour,

<CFMAX> is the maximum (design) cfm for the zone,

<EXHAUST-CFM> is the exhaust air fan cfm for the zone,

MULTIPLIER is the number of zones with like conditions,

CFM is the total supply air for the system, which is expressed as

$$\text{CFM} = \sum_{nz=1}^{nzone} (\text{<CFMAX>} * \text{CFMDIV} - \text{EXHAUST-CFM}) * \text{MULTIPLIER},$$

ECFM is the total exhaust air from the system, which is expressed as

$$\text{ECFM} = \sum_{nz=1}^{nzone} \text{EXHAUST-CFM} * \text{MULTIPLIER},$$

QP is the heat gain to the plenum(s) from lights, which is expressed as

$$QP = \sum_{nz=1}^{nzone} \text{<QP>} * \text{MULTIPLIER or 0 if RETURN-AIR-PATH = DIRECT, and}$$

CONS(1) is a factor that converts cfm-°F to Btu/hr.

The temperature of air leaving the plenum(s) (TRP) can be estimated by using the last hour's value of zone temperature plus the change from the previous two hours.

$$\text{TRP} = \frac{\displaystyle\sum_{\text{II}=1}^{\text{No. of Plenums}} [\text{<TNOW>} + (\text{<TNOW>} - \text{<TPAST>})] * \text{MULTIPLIER} * \text{<AREA>}}{\text{<PLENMULT>}}, \qquad \text{(IV.553)}$$

where

<TNOW> is the zone temperature, left over from the last hour's calculation,

<TPAST> is the zone temperature for the hour before last, also left over from the previous calculation,

<AREA> is the plenum zone floor area, and

$$\text{<PLENMULT>} = \sum_{\text{II}=1}^{\text{No. of Plenums}} \text{MULTIPLIER} * \text{<AREA>}.$$

The return air temperature can then be calculated using the results of Eqs. (IV.552) and (IV.553) as follows:

$$\text{TR} = \text{TRP} + \text{RETURN-DELTA-T} \qquad \text{(IV.554)}$$

if the return air fan(s) were running the previous hour

and

$$\text{TR} = \left\{[\text{TRP} + \text{TR}_{\text{from Eq. (IV.552)}}] * 0.5\right\} + \text{RETURN-DELTA-T} \qquad \text{(IV.555)}$$

if the return air fan(s) were off the previous hour, where

RETURN-DELTA-T = the temperature gain from the return air fan divided by CONS(3).

Step 2. Estimate the Mixed Air Temperature Limits

The limits of the mixed air temperatures are next calculated. This is done so that when heating and/or cooling are not available from the coils, the available temperature range for ventilation is known. This range will also be used to ensure that the use of last hour's mixed air temperature, if the fans were on, can be used to estimate this hour's mixed air temperature. It is also necessary to calculate the temperature of the mixed air when the outside air dampers are set at the minimum position. This value will be used for the single zone simulations (SZRH and PSZ) when the zone temperature is calculated to be in the deadband between the heating and cooling THROTTLING-RANGEs.

First, it is necessary to adjust the total supply air volume for the system, CFM from Eq. (IV.552), for leakage by dividing by (1.0 - <DUCT-AIR-LOSS>). Then, the minimum outside air damper setting (POM) is set as

$$\text{POM} = \text{<MIN-OUTSIDE-AIR> or <MIN-AIR-SCH>, if specified.} \tag{IV.556}$$

It is now possible to calculate the minimum fraction of CFM that must be outside air, assuming the minimum fraction from Eq. (IV.556) must always be supplied as a part of the design air supply, as

$$\text{POMIN} = \frac{\text{larger of (ECFM) or (POM * SUPPLY-CFM)}}{\text{CFM}} . \tag{IV.557}$$

The mixed air temperature at the minimum damper position,

$$\begin{aligned}\text{TPOMIN} = &\left\{[\text{SUPPLY-DELTA-T} * \text{CONS(3)}] + \text{DUCT-DELTA-T}\right\} + \text{the larger of} \\ &\left\{(\text{POMIN} * \text{DBT}) + (1.0\text{-POMIN}) * \text{TR}]\right\} \underline{\text{or}} \text{ (PREHEAT-T, if heating is on),}\end{aligned} \tag{IV.558}$$

where

DBT is the outside dry-bulb temperature,

PREHEAT-T is the air temperature leaving the active preheat coil,

SUPPLY-DELTA-T is the temperature rise across the supply air fan, and

DUCT-DELTA-T is the temperature change in the supply air duct.

The maximum outside air quantity is

$$POMAX = POMIN, \text{ if OA-CONTROL = FIXED or } POMIN = 0.0 \tag{IV.559}$$

otherwise,

$$POMAX = \text{MAX-OA-FRACTION}.$$

The minimum and maximum mixed air temperatures (TMMAX and TMMIN respectively) are then

$$TMMAX = DTF + \left\{(POMAX * DBT) + [(1.0 - POMAX) * TR]\right\} \tag{IV.560}$$

and

$$TMMIN = DTF + \text{the larger of } \left\{(POMIN * DBT) + [(1.0\text{-}POMIN) * TR]\right\} \; \underline{\text{or}} \; [\text{PREHEAT-T}] \tag{IV.561}$$

where

$$DTF = \text{SUPPLY-DELTA-T, if FAN-PLACEMENT = BLOW-THROUGH}$$

<u>or</u>

$$DTF = 0.0, \text{ if FAN-PLACEMENT = DRAW-THROUGH.}$$

<u>Step 3. Calculate the Minimum Supply Air Temperature</u>

The minimum supply air temperature that can be provided (TCMIN) is calculated such that, when the controller action is simulated, the controller is not allowed to request cooler air than is possible.

If the fans were off the previous hour, it is necessary to first estimate the mixed air temperature that would have occurred the previous hour had the fans been on. To do this, a supply air temperature will be assumed as

$$TC = \text{MIN-SUPPLY-T} - \text{DUCT-DELTA-T} - \text{SUPPLY-DELTA-T} \tag{IV.562}$$

where

MIN-SUPPLY-T is the lowest possible air temperature supplied to the zone.

However, if SYSTEM-TYPE = HVSYS and DBT < TR,

TC = MAX-SUPPLY-T + DUCT-DELTA-T - SUPPLY-DELTA-T.

This, essentially, assumes the worst case when the fans restart in the morning or for a nighttime cycling.

Next, the economizer routine is called with TC and POM as input. This subroutine will calculate the outside air fraction (PO) and the mixed air temperature (TM). DTF is then added to TM and the sum is saved as <PASTMIX>, the past hour's value of mixed air temperature. It is also necessary to estimate the mixed air wet-bulb temperature because it will affect the cooling coil capacity (20 percent migration of the return air humidity ratio towards the current outdoor air humidity ratio is allowed for each hour the fans are off). The return air condition calculated in this manner, along with the PO calculated by the economizer routine, are used to calculate a wet-bulb temperature that is saved as <PASTMIXW> (the previous hour's mixed air wet-bulb temperature).

The last step in this startup initialization is to estimate the cold deck controller action. This is done by using the values of TM and TC plus the design sensible cooling capacity of the coil (COOL-SH-CAP) to estimate the part-load ratio (<PASTPLRC>) that will be "seen" by the controller.

$$\langle \text{PASTPLRC} \rangle = \frac{(\text{TM}-\text{TC}) * \text{CONS}(1) * \text{SUPPLY-CFM}}{\text{COOL-SH-CAP}} \quad . \qquad \text{(IV.563)}$$

The controller for the cold supply air temperature has a throttling range within which it will cause the cooling device (coil or compressor) to produce between 0 and 100 percent of its capacity. The program simulates the throttling range of this controller (COOL-CTRL-RANGE) as being centered around the set point temperature. The set point location in °F, as a function of time, is governed by the strategy specified in the keyword COOL-CONTROL and its associated keywords. The strategies are specified via the code-words SCHEDULED, WARMEST, RESET, and CONSTANT. Because the exact operation of the controller (output signal) would require a simultaneous solution of all zones and system performance, the past hour's sensible part-load ratio of the coil (<PASTPLRC>) is used to calculate the current hour's output signal (TRC).

$$\text{TRC} = \text{COOL-CTRL-RANGE} * (\langle \text{PASTPLRC} \rangle - 0.5) \qquad \text{(IV.564)}$$

TRC is then added to the set point temperature, except for WARMEST and COLDEST control because these types of controls act directly with the zone thermostats.

The total cooling capacity (QCT) and the sensible cooling capacity (QCS) are

$$\text{QCT} = \text{COOLING-CAPACITY} * \text{CVAL(COOL-CAP-FT,EWB,EDB)} \qquad \text{(IV.565)}$$

and

$$\text{QCS} = [\text{COOL-SH-CAP} * \text{CVAL(COOL-SH-FT,EWB,EDB)}] + \text{QCSADJ} \qquad \text{(IV.566)}$$

or QCT, whichever is smaller,

where

COOLING-CAPACITY is the total, or rated, capacity of the cooling coil or the cooling system,

CVAL(COOL-CAP-FT, EWB, EDB) is the correction value to the total, or rated, cooling capacity for non-rated humidity conditions,

COOL-SH-CAP is the sensible heat removal capacity of the cooling system at ARI rated conditions,

CVAL(COOL-SH-FT, EWB, EDB) is the correction value to the sensible heat removal capacity for non-rated humidity conditions,

EWB is the entering wet-bulb temperature for the last hour <PASTMIXW> or 60.0, whichever is larger,

EDB is the dry-bulb reference temperature (which is <PASTMIX> for builtup systems or DBT for packaged systems) or COOL-FT-MIN, whichever is larger, and

QCSADJ is 0.0 for builtup systems, or [CONS(1) * SUPPLY-CFM * (1.0 - COIL-BF) * (<PASTMIX> - 80)] for packaged systems.

COIL-BF is the rated coil bypass factor. Note that the adjustment for a packaged system entering dry-bulb temperature (QCSADJ) assumes an entering dry-bulb rating temperature at 80°F. This is a requirement of all data entered for packaged systems. The minimum supply temperature (TCMIN) is now calculated as

$$\text{TCMIN} = \text{<PASTMIX>} - \frac{\text{QCS}}{\text{CONS(1)} * \text{(larger of <PASTCFM> or <SUPPLY-CFM>)}}, \qquad \text{(IV.567)}$$

if cooling is on (that is, the cooling flag CON = 1.0). If cooling is off, TCMIN is set equal to TMMIN, the minimum mixed air temperature obtainable. The values of TCMIN, TMMIN, TMMAX, and THMAX (which is set equal to TMMAX at this point) are now converted to supply air temperatures by adding DUCT-DELTA-T and the temperature rise caused by the supply fan heat gain, if FAN-PLACEMENT equals DRAW-THROUGH. Then, it is assured that TCMIN is not less than <MIN-SUPPLY-T> - TRC.

Step 4. Calculate the Cold Duct Supply Air Temperature

The cooling controller set point temperature is determined by the COOL-CONTROL and its related values. Both COOL-CONTROL and HEAT-CONTROL can have the values 0, 1, 2, 3, 4, and 6, which mean respectively no controller, CONSTANT, COLDEST, WARMEST, RESET, and SCHEDULED.

A. If COOL-CONTROL = CONSTANT, the subroutine sets TC equal to the larger of (COOL-SET-T + TRC) or TCMIN.

B. If COOL-CONTROL = SCHEDULED, TC is set to the larger value for the current hour of (COOL-SET-SCH + TRC) or TCMIN.

C. The warmest zone in the system controls the supply air temperature when COOL-CONTROL = WARMEST.

   Before reading this section, the reader should understand Sec. IV.4.1, entitled "Interface Between LOADS and SYSTEMS (subroutine TEMDEV)." This control simulation takes the signal from the zone whose temperature is highest in its cooling throttling range, and uses that zone signal to control the cooling supply air temperature. To simulate this interaction of zone thermostats and cold deck controller adequately, it is necessary to solve the zone temperature and thermostat-action equations, together with the supply air temperature control. This process is complicated when a variable-air-volume capability is specified. As discussed in Sec. IV.4.1, the situation is simplified by assuming a linear thermostat action. A linear cold deck controller action is also assumed. In the case of VAV terminals located in the zone, the bottom half of the cooling throttling range is used for supply air temperature reset (with volume flow at its minimum) and the top half is used for volume reset (with the temperature at its minimum). For each zone, the calculations described below are performed.

   If it is assumed that the supply air temperature and flow rate, as well as the zone temperature, are constant throughout the hour, the maximum heat extraction rate and the minimum heat extraction rate can be calculated, based upon the minimum supply temperature (TCMIN) and the maximum supply air temperature. This latter temperature can be described as the mixed air temperature when the outside air dampers are at their minimum position and the cooling coil is not active, TPOMIN.

$$\text{ERMAX} = \text{CONS}(1) * \text{<CFMAX>} * \text{<MINCFMR>} * (\text{<TNOW>} - \text{TCMIN}) \qquad \text{(IV.568)}$$

$$\text{ERMIN} = \text{CONS}(1) * \text{<CFMAX>} * \text{<MINCFMR>} * (\text{<TNOW>} - \text{TPOMIN}) \qquad \text{(IV.569)}$$

The equation that relates the zone temperature, at the end of the hour, to the heat extraction capacity, based on the zone temperature at the beginning of the hour (as described in Sec. IV.4.1.3), is Eq. (IV.570). This equation is shown for the case where the supply air flowing into the space is at both minimum temperature and flow rate.

$$TEND = \frac{F - ERMAX + (Z * <TNOW>)}{GO + Z}, \tag{IV.570}$$

where F and GO are as defined in Sec. IV.4.1 and
$$Z = CONS(1) * <CFMAX> * <MINCFMR> * 0.5.$$

The thermostat set point (TSET) and the half-throttling range (THR) are, for constant volume zones, equal to the value referenced by COOL-TEMP-SCH and half of the THROTTLING-RANGE, respectively. For variable volume zone terminal units, TSET is set equal to the value referenced by COOL-TEMP-SCH minus one-fourth of the value of THROTTLING-RANGE. Also, THR is set equal to one-fourth of THROTTLING-RANGE. This ensures that temperature reset occurs only in the bottom half of the throttling range.

If the value calculated for TEND by Eq. (IV.570) is greater than TSET + THR, then the signal from this zone will cause the temperature to be at its minimum (TCMIN). If the temperature of any zone is above TSET + THR, this will be true. Otherwise, the zone whose temperature is at the highest relative position in the range TSET - THR to TSET + THR.

Because, at this point, it is known that the temperature will be within or below the reset range, the zone temperature equations must be solved together with the supply air reset (volume reset between TSET and TSET + THR and temperature reset between TSET and TSET - THR). Assuming a linear relation between zone temperature and extraction rate, to calculate the slope and intercept requires correcting the maximum and minimum extraction rates from Eq. (IV.568) and Eq. (IV.569) to reflect the zone temperature swing during the hour. ERMAX is corrected using the value of TEND from Eq. (IV.570)

$$ERMAX = ERMAX_{(IV.570)} - [Z * (<TNOW> - TEND)]. \tag{IV.571}$$

Similarly, recalculating TEND, by substituting ERMIN for ERMAX in Eq. (IV.570), allows the recalculation of ERMIN, as in Eq. (IV.571) by substituting ERMIN for ERMAX. Then the slope (S) and intercept (W) of the equation of supply air/room extraction vs. thermostat temperature signal can be calculated.

$$Q = W + (S * T), \tag{IV.572}$$

where Q = the extraction rate caused by supply air temperature,

$$S = \frac{ERMAX - ERMIN}{THR * 2.0},$$

$$W = \frac{ERMAX + ERMIN}{2.0} - (S * TSET), \text{ and}$$

T = the current hour's zone temperature.

$$Q = F - (GO * T) \qquad (IV.573)$$

represents the zone temperature/extraction rate weighting factor relationship.

Combining Eq. (IV.572) and Eq. (IV.573), and then solving first for Q, gives Eq. (IV.574) for the extraction rate and Eq. (IV.575) for the resulting zone temperature

$$Q = \frac{(GO * W) + (S * F)}{S + GO} \text{ and} \qquad (IV.574)$$

$$T = \frac{F - Q}{GO} . \qquad (IV.575)$$

Note that Q must be constrained between ERMIN and ERMAX because steady state solution may not exist within the throttling range. The signal to the coil reset controller, resulting from this zone thermostat, is TSIG

$$TSIG = \frac{T - TSET}{THR} . \qquad (IV.576)$$

This value is held within the range -1 to +1 to indicate a full off to full on signal, respectively. If all zone temperatures thus predicted are below the top of the throttling range, the zone whose TSIG is the largest is used to calculate the supply air temperature

$$TC = \frac{T + \langle TNOW \rangle}{2.0} - \left(\frac{Q}{Z * 2.0}\right) . \qquad (IV.577)$$

In Eq. (IV.577) the average zone temperature minus the temperature difference needed to obtain a net extraction of Q is used to calculate the required supply air temperature. The value of TC is constrained between TCMIN, as a minimum, and TPOMIN, as a maximum.

D. If COOL-CONTROL = RESET, TC is calculated as

$$TC = \frac{SL - SH}{RH - RL} * (DBT - RL), \tag{IV.578}$$

where

SL = SUPPLY-LO from COOL-RESET-SCH,
SH = SUPPLY-HI from COOL-RESET-SCH,
RL = OUTSIDE-LO from COOL-RESET-SCH, and
RH = OUTSIDE-HI from COOL-RESET-SCH,

assuming DBT is within the range defined by OUTSIDE-LO and OUTSIDE-HI. If DBT is above this range, TC = SL and if DBT is below this range, TC = SH.

Use of the keyword MAX-HUMIDITY may require the value specified for COOL-CONTROL to be overridden, to control the zone humidity.

The value specified for MAX-HUMIDITY is the relative humidity that the user wishes not to be exceeded. This control simulation attempts to maintain the specified value of MAX-HUMIDITY as an upper limit, as measured in the return air stream.

The strategy used for simulating this control is as follows: First, the maximum cooling coil exit humidity ratio, to maintain the specified return air humidity ratio, is calculated. The mixed air humidity ratio is also calculated. If the mixed air humidity ratio is less than or equal to the maximum coil exit humidity ratio allowable, this controller has no effect this hour and the program skips to the normal controller simulation, specified through the use of the keyword COOL-CONTROL. Starting with the moisture balance relation derived in Sec. IV.1, the relation presented in Eq. (IV.16) can be produced. Expressing Eq. (IV.16) in terms of the maximum return air humidity ratio, allowing for the specified MAX-HUMIDITY, gives Eq. (IV.579)

$$WRMAX = \frac{WCOL + (F * HUMRAT) + DW}{1.0 + F} . \tag{IV.579}$$

Rearranging this, in terms of the maximum coil exit condition allowed, gives Eq. (IV.580)

$$WCOL = [(1.0 + F) * WRMAX] - DW - (F * HUMRAT). \tag{IV.580}$$

The relation for the mixed air condition, in terms of outside and return air conditions, is shown in Eq. (IV.581)

$$WM = (POMIN * HUMRAT) + [(1.0 - POMIN) * WRMAX]. \qquad (IV.581)$$

Note that this assumes that the outside air dampers are at their minimum position (POMIN) for this calculation. If WM is less than or equal to WCOL, no temperature depression of the coil is necessary. Otherwise, the maximum coil exit air temperature that will allow for the proper humidity control, TCHUM, must be calculated. After this temperature is calculated, the cooling coil control specified through the keyword COOL-CONTROL is simulated and the lower of the resultant temperature and TCHUM is used as the actual supply air temperature.

To calculate the cooling coil temperature required for humidity control, TCHUM, the coil exit air conditions, when the coil is supplying the lowest obtainable temperature, TCMIN, must first be calculated. Using the bypass relationship [Eq. (IV.11)], the coil surface temperature can be calculated from the supply temperature

$$TSURFM = \frac{TCMIN - [CBF * <PASTMIX>]}{1.0 - CBF}\ , \qquad (IV.582)$$

where $CBF = COIL\text{-}BF * CVAL(COIL\text{-}BF\text{-}FT,EWB,EDB)$
$\qquad\qquad * CVAL(COIL\text{-}BF\text{-}FT,<PASTCFM>/RATED\text{-}CFM).$

Knowing TSURFM, the saturation humidity ratio, WSURFM, at this temperature can be calculated. Then, combining Eq. (IV.581) with Eq. (IV.19) and Eq. (IV.12), it is possible to solve for the coil exit humidity ratio at the minimum supply air temperature.

$$WCOLM = \frac{A + B + C}{1.0 + F - [CBF * (1.0 - POMIN)]}\ , \qquad (IV.583)$$

where

$A = [(F + POMIN) * CBF * HUMRAT],$
$B = [(1.0 - POMIN) * CBF * DW]$, and
$C = [(1.0 - CBF) * WSURFM].$

If WCOL, the required coil exit humidity ratio, is less than or equal to WCOLM, WCOL is not maintainable and as such is reset to WCOLM. If this is the case, the temperature of the coil exiting air is the minimum supply temperature, TCMIN (the program then skips to the cold deck controller simulation). If WCOL is greater than WCOLM, the coil surface saturation humidity ratio, WSURF, required to produce an exit condition of WCOL is calculated. This is done by rearranging Eq. (IV.583)

$$WSURF = \frac{A - B - C}{(1.0 - CBF)} , \qquad (IV.584)$$

where

$$A = WCOL * \{1.0 + F - [CBF * (1.0 - POMIN)]\},$$
$$B = [(F + POMIN) * CBF * HUMRAT], \text{ and}$$
$$C = [(1.0 - POMIN) * CBF * DW].$$

Next, starting with the minimum surface temperature, TSURFM, the program increases the temperature one degree at a time until the two temperatures that have saturation humidity ratios that bracket the required value are found. The required surface temperature, TSURF, is then calculated by linear interpolation between these two temperature values, based on the required surface saturation humidity ratio and the two bracketing surface saturation humidity ratios. The required supply temperature, TCHUM, is then calculated, using the bypass relation

$$TCHUM = [TSURF * (1.0 - CBF)] + (<PASTMIX> * CBF) \qquad (IV.585)$$

The cold deck controller simulation, specified by the keyword COOL-CONTROL, is then performed and the resultant temperature is tested to insure that it is less than or equal to TCHUM, just calculated.

Step 5. Calculate the Maximum Supply Air Temperature

The maximum heating supply air temperature (THMAX) is now calculated to ensure that the hot deck controller simulation does not supply air at a higher temperature than the heating coil can provide. THMAX is initialized to TCMIN, calculated previously. If the heating is scheduled to be on, then the heating capacity (QHT) is set to HEATING-CAPACITY, except when the HEAT-SOURCE equals HEAT-PUMP in which case the capacity is calculated as

$$QHT = QHP + QHE, \qquad (IV.586)$$

where

QHP is HEATING-CAPACITY * CVAL(HEAT-CAP-FT), DBT + (70.0 - <PASTMIX>), assuming DBT is larger than MIN-HP-T, but

QHP is 0.0 if DBT is less than MIN-HP-T, and

QHE is ELEC-HEAT-CAP assuming DBT is less than MAX-ELEC-T, but

QHE is 0.0, if DBT is larger than MAX-ELECT-T, HEATING-CAPACITY is the total, or rated, capacity of the heat pump,

HEAT-CAP-FT is a correction function to the total, or rated, heating capacity for non-rated dry-bulb temperatures,

ELEC-HEAT-CAP is the total, rated, heat capacity of the electric resistance heater in the heat pump, and

MAX-ELEC-T is the maximum outdoor dry-bulb temperature above which the electric resistance heater is turned off.

Now, it is possible to calculate

$$\text{THMAX} = \left[\text{<PASTMIX>} - \frac{\text{QHT}}{\text{CONS(1)} * \text{<CFMH>}} \right] - \text{DUCT-DELTA-T} + \text{QF}, \qquad \text{(IV.587)}$$

where

<CFMH> is the heating supply air flow rate, and

QF = SUPPLY-DELTA-T * CONS(3), assuming the FAN-PLACEMENT equals DRAW-THROUGH, but

QF = 0.0 if FAN-PLACEMENT equals BLOW-THROUGH.

If heating is scheduled to be off and the SYSTEM-TYPE is not SZRH, PSZ, or HVSYS, THMAX is set to the larger of TMMIN and the lesser of TC or TMMAX. THMAX must be within the range determined by TCMIN and MAX-SUPPLY-T.

Step 6. Calculate the Hot Duct Supply Air Temperature

Again, as with the TC calculation, no value of TH, calculated for the heating controller set point temperature, will be allowed to exceed THMAX. Likewise, if the SYSTEM-TYPE is not HVSYS, no value of TH will be allowed to go below the maximum of TMMIN and the lesser of TC or TMMAX.

A. If HEAT-CONTROL = CONSTANT or SCHEDULED, the subroutine sets TH to HEAT-SET-T or to the current hour's value of HEAT-SET-SCH.

B. The coldest zone in the system controls the supply air temperature when HEAT-CONTROL = COLDEST.

This control simulation is similar to the simulation described in this section (Step 4) for the WARMEST control. Here, however, the hot supply air temperature is being reset between a maximum value of THMAX and a minimum value of THMIN. THMIN is normally the maximum obtainable mixed air temperature TMMIN (described earlier) for SYSTEM-TYPE = HVSYS, or the actual mixed air temperature for other types of systems.

In this control simulation, the entire throttling range is used for the reset, unless a variable volume capability is specified in conjunction with a REVERSE-ACTION thermostat. For the latter case, the bottom half of the HEAT-TEMP-SCH THROTTLING-RANGE is used for volume control (minimum to maximum volume as the temperature decreases from the midpoint to the bottom of the throttling range) and the top half of the throttling range is used for temperature control (minimum to maximum, at minimum volume flow, as the temperature decreases from the top to the midpoint of the throttling range).

As described in Step 4 of this section, the maximum and minimum heat extraction rates for the zone are first calculated. This is done by substitution of THMIN for TCMIN in Eq. (IV.568) and THMAX for TPOMIN in Eq. (IV.569). The zone temperature resulting from the maximum supply temperature is calculated by substituting ERMIN, just described, for ERMAX in Eq. (IV.570). If this temperature is less than the temperature at the bottom of the control range, this zone will force the supply air temperature of the system to its maximum.

$$\mathrm{ERMAX} = \mathrm{CONS}(1) * <\mathrm{CFMAX}> * <\mathrm{MINCFMR}> * (<\mathrm{TNOW}> - \mathrm{THMIN}) \qquad \text{(IV.588)}$$

$$\mathrm{ERMIN} = \mathrm{CONS}(1) * <\mathrm{CFMAX}> * <\mathrm{MINCFMR}> * (<\mathrm{TNOW}> - \mathrm{THMAX}) \qquad \text{(IV.589)}$$

$$\mathrm{TEND} = \frac{\mathrm{F} - \mathrm{ERMIN} + (\mathrm{Z} * <\mathrm{TNOW}>)}{\mathrm{GO} + \mathrm{Z}}, \qquad \text{(IV.590)}$$

where F and GO are as described in Sec. IV.4.1 and
$\mathrm{Z} = \mathrm{CONS}(1) * <\mathrm{CFMAX}> * <\mathrm{MINCMFR}> * 0.5$.

If no zone temperature is at or below the bottom of the control range, the zone sending the lowest signal, determined by its temperature's relative position in the control range, must be found. First, ERMAX and ERMIN must be adjusted for the temperature swing that would take place within the hour [Eq. (IV.571)]. Then the slope and intercept of the equation, which relates zone temperature to supply air extraction rate, Eq. (IV.572), are calculated. This equation is then solved together with the zone temperature/extraction weighting factor relation, Eq. (IV.573), for the zone extraction rate and temperature, Eq. (IV.574) and Eq. (IV.575), respectively. The thermostat signal is then determined using Eq. (IV.576) and the zone with the <u>lowest</u> signal is found and used to reset the supply air temperature

$$\mathrm{TH} = \frac{\mathrm{T} + <\mathrm{TNOW}>}{2.0} - \left(\frac{\mathrm{Q}}{\mathrm{Z} * 2.0}\right). \qquad \text{(IV.591)}$$

Note that the average zone temperature minus the temperature difference needed to obtain a net extraction of Q [from Eq. (IV.574)] is used here. This value is constrained between THMIN and THMAX.

C. If HEAT-CONTROL equals RESET, a similar procedure is followed, as described previously for COOL-CONTROL = RESET, except using HEAT-RESET-SCH values.

If a hot duct controller is not present (not a HVSYS, MZS, PMZS, or DDS), TH is not set.

4.4. Outside Air Control (subroutine ECONO)

The subroutine ECONO is called to calculate the outside air damper position and the mixed air temperature. The subroutine requires, as input from other subroutines, the mixed air controller set point temperature (TAPP) and the minimum damper position (POM).

Calculation outline

1. Determine the type of outside air control and calculate the mixed air temperature.
2. Calculate the heat recovery addition to the mixed air temperature.

Calculation algorithms

Step 1. Determine the Type of Outside Air Control and Calculate the Mixed Air Temperature

The value of POM, the minimum damper position, will be 0.0 if the system has no outside ventilation air dampers. In this case, PO, the fraction of outside air in the zone supply air, is set to 0.0 and TM, the mixed air temperature, is set to TR, the return air temperature. However, if POM is greater than 0.0, there exists outside ventilation air dampers, either fixed-position or movable.

If, in the SYSTEM-AIR instruction, the keyword OA-CONTROL = FIXED, the system does not have movable dampers. PO is set to POM and the mixed air temperature (TM) is calculated as

$$TM = (PO * DBT) + [(1.0 - PO) * TR]. \tag{IV.592}$$

If movable dampers exist (OA-CONTROL = TEMP or ENTHALPY), the subroutine then checks to see if the outdoor dry-bulb temperature (DBT) is larger than ECONO-LIMIT-T. If this is true, PO is set to POM and the mixed air temperature is calculated by Eq. (IV.592). Otherwise, the mixed air controller set point temperature (TAPP) is used to calculate the fraction of outside air (PO) as

$$PO = \frac{TAPP - TR}{DBT - TR}, \tag{IV.593}$$

assuming this calculated value of PO lies within the range defined by POM and MAX-OA-FRACTION, however,

PO = POM, if the calculated value of PO lies below this range, and

PO = MAX-OA-FRACTION, if the calculated value of PO lies above this range.

If the OA-CONTROL equals ENTHALPY and the enthalpy calculated from TR and last hour's return air humidity ratio is larger than the outdoor enthalpy, PO is set to POM. In any case, TM is again calculated from Eq. (IV.592).

Step 2. Calculate the Heat Recovery Addition to the Mixed Air Temperature

If

(a) RECOVERY-EFF has been specified,
(b) PO is not equal zero,
(c) TM is not greater than TAPP, and
(d) the return air temperature is more than 10 degrees above the outdoor dry-bulb temperature,

the heat recovery system is activated. The temperature (DTREC) obtainable downstream of the recovery coils in the outside air duct is the outdoor dry-bulb temperature plus the ratio of mass flow rates of the central exhaust (relief) air to the outside ventilation air times the product of the temperature difference (TR-DBT) and the central exhaust heat recovery system effectiveness (RECOVERY-EFF). The mass flow rate of outside ventilation air is PO * CFM. The mass flow rate of central exhaust (relief) air is the outside airflow rate, adjusted for duct air losses and zone exhaust. Thus,

$$\text{DTREC} = \text{DBT} + \left[(1.0 - \text{DUCT-AIR-LOSS})\,\frac{\text{ECFM}}{\text{PO} * \text{CFM}}\right] * (\text{TR} - \text{DBT}) * \text{RECOVERY-EFF}. \tag{IV.594}$$

where

$$\text{ECFM} = \sum_{nz=1}^{nzones} \text{EXHAUST-CFM}_{nz} * \text{MULTIPLIER}_{nz}, \text{ and}$$

$$\text{CFM} = \frac{\sum_{nz=1}^{nzones} \text{supply air to zone}}{(1.0 - \text{DUCT-AIR-LOSS})},$$

where

nzones is the tota' number of zones in the system, and

MULTIPLIER is the number of zones with like conditions.

The mixed air temperature (TM) is then calculated as

$$TM = (DTREC * PO) + [(1.0 - PO) * TR], \text{ or } TAPP \tag{IV.595}$$

whichever is smaller.

4.5 Calculation of Fan Energy Consumption (subroutine FANPWR)

The subroutine FANPWR is called to calculate supply air fan and return air fan electrical energy use and also to calculate the ratio of fan heat gain this hour to that at design loading. The values SFKW and RFKW, the electrical kW for the supply air and return air fans respectively, are calculated and added to the total system electrical usage. The values PLS and PLR, the ratios of this hour's heat gain to design load heat gain for the supply fan and the return fan respectively, are calculated and passed as parameters to the calling subroutine.

Calculation Algorithm

If either the supply air fan or the return air fan flow rate is zero, the energy input and heat gain ratio for that fan are set to zero. If the flow rate is not zero, the fan part-load ratio is calculated as

$$PL_{supply} = CFM \;/\; \langle SUPPLY\text{-}CFM \rangle$$

or

$$PL_{return} = RCFM \;/\; \langle RETURN\text{-}CFM \rangle, \qquad \text{(IV.596)}$$

where

CFM is the supply air flow rate this hour,

RCFM is the return air flow rate this hour,

SUPPLY-CFM is the design, rated, capacity of the supply air fan, and

RETURN-CFM is the design, rated, capacity of the return air fan.

The calculated values are, however, constrained within the range from MIN-FAN-RATIO to MAX-FAN-RATIO. Thus, if the part-load ratio falls below MIN-FAN-RATIO, a fan bypass is simulated by holding fan air flow and power consumption constant. The part-load ratio of energy input to the supply air fan rated energy input (PWR_S) is then calculated as

$$PWR_S = 1.0 \text{ if FAN-CONTROL = CONSTANT-VOLUME, or} \qquad \text{(IV.597)}$$

$$PWR_S = CVAL\ (FAN\text{-}EIR\text{-}FPLR, PL_{supply}) \text{ if FAN-CONTROL = FAN-EIR-FPLR, or}$$

$$PWR_S = [PTLD(1,I)] + \{PL_{supply} * [PTLD(2,I)]\} + \{PL_{supply} * [PTLD(3,I)]\} + \{PL_{supply} * [PLTD(4,I)]\},$$

if FAN-CONTROL = SPEED, INLET, DISCHARGE, or CYCLING

where

FAN-CONTROL specifies the fan control strategy.

FAN-EIR-FPLR is a correction function, expressed as a function of part load, of the ratio of electric energy input to the fan to the rated load electric input to the fan, and

PLTD values are found in Table IV.2.

TABLE IV.2

COEFFICIENTS FOR CALCULATING THE PART-LOAD RATIO OF ENERGY INPUT FOR SUPPLY AIR AND RETURN AIR FANS BY FAN CONTROL STRATEGY

FAN-CONTROL(I)	PTLD(1,I)	PTLD(2,I)	PTLD(3,I)	PTLD(4,I)
SPEED(1)	0.00153028	.00520806	1.1086242	-0.11635563
INLET(2)	0.35071223	0.3080535	-0.5413736	0.87198823
DISCHARGE(3)	0.37073425	0.97250253	-0.3424076	0.0
CYCLING(4)	0.0	1.0	0.0	0.0

The part-load ratio of energy input to the return air fan (PWR_r) is calculated the same as for PWR_s.

Now, it is possible to calculate fan energy consumptions as

$$SFKW = <SUPPLY\text{-}KW> * PWR_s \qquad (IV.598)$$

and

$$RFKW = <RETURN\text{-}KW> * PWR_r .$$

See Eq. (IV.35) and Eq. (IV.42) for the calculated values of SUPPLY-KW and RETURN-KW, respectively.

The total fan energy consumption is then calculated as

$$FANKW = SFKW + RFKW \qquad (IV.599)$$

and is added to the total system electrical energy consumption (<SKW>).

The ratios of part-load energy consumptions to part-load flow are then

$$PLS = \frac{PWR_s}{PL_{supply}}, \text{ for supply air fans}$$

and

$$PLR = \frac{PWR_r}{PL_{return}}, \text{ for return air fans} \qquad \text{(IV.600)}$$

This is used as the ratio of operating-to-design fan heat gain.

4.6 Calculation of Wet-Bulb Temperature (subroutine WBFS)

The routine WBFS calculates the wet-bulb temperature, given the dry-bulb temperature (T), humidity ratio (W), and the atmospheric pressure (PB).

Calculation Outline

Calculate the wet-bulb temperature in ranges for:

1. negative enthalphy,
2. atmospheric pressure within ± 5 percent of standard atmospheric pressure, and
3. nonstandard atmospheric pressure.

Calculation Algorithm

Step 1. Negative Enthalphy

If the enthalphy of the air is less than 1.0, the wet-bulb temperature is set to zero. This low wet-bulb temperature is not important because the wet-bulb temperature is only used for adjusting cooling equipment capacity.

Step 2. Atmospheric Pressure Within ± 5 Percent of Standard Atmospheric Pressure

If the atmospheric pressure is within ± 5 percent of standard atmospheric pressure (28.5 to 31.5 in. Hg.), the following curve fit is used

$$WBFS = A + Y[B + Y(C + Y * D)], \tag{IV.601}$$

where

Y is the logrithm of the enthalpy of the air at dry-bulb temperature T and humidity ratio W, and

A, B, C, and D are from Table IV.3.

TABLE IV.3

COEFFICIENTS FOR CALCULATING THE WET-BULB TEMPERATURE IF THE ATMOSPHERIC PRESSURE IS WITHIN ± 5 PERCENT OF STANDARD ATMOSPHERIC PRESSURE

	A	B	C	D
H1 $\leq$ 11.758	0.6041	3.4841	1.3601	0.97307
H1 > 11.758	30.9185	-39.682	20.5841	-1.758

Step 3. Nonstandard Atmospheric Pressure

For nonstandard atmospheric pressures, the subroutine calculates the enthalphy of the air at saturation for successively lower values of T, the dry-bulb temperature. When the subroutine finds the two temperatures that bracket the enthalpy at T and W, the subroutine interpolates between them to calculate WBFS. Thus,

H1 = H [T,W], the enthalpy of T and W,

$$H2 = H\left[T_1, \frac{0.622 * PPWVMS(T)}{PB-PPWVMS(T)}\right], \tag{IV.602}$$

$$H3 = H\left[T_1 - 1, \frac{0.622 * PPWVMS(T - 1)}{PB-PPWVMS(T - 1)}\right],$$

etc.,

where PPWVMS(T) is found in Table IV.4 and is used to calculate a new value of W.

If H3 is greater than H1, the subroutine will decrement T_1 by one and check again. If H3 is less than H1, the subroutine calculates

$$WBFS = (T_1 - 1) + \frac{(H1 - H3)}{(H2 - H3)}. \tag{IV.603}$$

4.7 Calculation of Humidity Ratio (subroutine WFUNC)

The function of the subroutine WFUNC is to calculate the humidity ratio (lb of H_2O/lb of dry air) for a given dry-bulb temperature (TEMP), relative humidity (RH), and atmospheric pressure (PRESS).

Calculation Outline

Find the dry-bulb temperature interval in columns 2 through 5 of Table IV.4 that brackets TEMP and interpolate to find WFUNC.

Calculation Algorithm

Step 1

The subroutine searches columns 2 through 5 of Table IV.4 for the dry-bulb temperature (IT) just below TEMP. A check is made to assure that IT is within the range of 1.0°F to 119.0°F. Next, to find the interpolated value of PPWVMS in the table, the subroutine determines the temperature difference (DT) between the actual dry-bulb temperature (TEMP) and IT as

$$\mathrm{DT} = \mathrm{TEMP} - \mathrm{IT}. \qquad \text{(IV.604)}$$

Now the subroutine finds the partial pressure of water vapor at saturation (PPW) as

$$\mathrm{PPW} = \mathrm{PPWVMS(IT)} + \left\{\mathrm{DT} * [\mathrm{PPWVMS(IT + 1)} - \mathrm{PPWVMS(IT)}]\right\}, \qquad \text{(IV.605)}$$

where the values of PPWVMS (for IT and IT + 1) are found in Table IV.4.

The subroutine then calculates the ratio of water vapor mass to air mass as

$$\mathrm{WFUNC} = 0.622 * \left[\frac{0.01 * \mathrm{RH} * \mathrm{PPW}}{\mathrm{PRESS} - (0.01 * \mathrm{RH} * \mathrm{PPW})}\right]. \qquad \text{(IV.606)}$$

TABLE IV.4

INTERPOLATION TABLE FOR PARTIAL PRESSURE OF WATER VAPOR (PPWVMS) FOR SATURATED AIR

DBT°F	+1°F	+2°F	+3°F	+4°F
0	.04031028	.04246103	.04471645	.04708111
4	.04955977	.05215739	.05487907	.05773016
8	.06071618	.06384287	.06711616	.07054224
12	.07412750	.07787858	.08180235	.08509593
16	.09019673	.09468238	.09937082	.10427026
20	.10938918	.11472640	.12032103	.12615248
24	.13224052	.13859523	.14522706	.15214680
28	.15936561	.16689504	.17474700	.18264669
32	.19014214	.19790889	.20595534	.21429014
36	.22292213	.23186038	.24111418	.25069306
40	.26060677	.27086531	.28147892	.29245808
44	.30381353	.31555625	.32769750	.34024879
48	.35322191	.36662889	.38048209	.39479411
52	.40957784	.42484650	.44061355	.45689279
56	.47369832	.49104452	.50894614	.52741819
60	.54647605	.56613540	.58641227	.60732303
64	.62888439	.65111340	.67402748	.69764440
68	.72198230	.74705968	.77289542	.79950879
72	.82691943	.85514738	.88421306	.91413732
76	.94494137	.97664689	1.00927592	1.04285096
80	1.07739492	1.11293114	1.14948342	1.18707597
84	1.22573347	1.26548105	1.30634431	1.34834928
88	1.39152250	1.43589096	1.48148215	1.52832402
92	1.57644505	1.62587418	1.67664086	1.72877508
96	1.78230731	1.83726854	1.89369031	1.95160467
100	2.01104421	2.07204206	2.13463190	2.19884796
104	2.26472504	2.33229848	2.40160421	2.47267871
108	2.54555908	2.62028296	2.69688861	2.77541487
112	2.85590120	2.93838765	3.02291489	3.10952421
116	3.19825751	3.28915734	3.38226686	3.47762989

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V. PLANT SIMULATOR
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1. PLANT OVERVIEW
by Steven D. Gates and Stephen C. Choi

1.1 Overview of PLANT Simulation

The PLANT program simulates primary HVAC equipment, i.e., central boilers, chillers, cooling towers, electrical generators, pumps, heat exchangers, and storage tanks. In addition, it also simulates domestic or process water heaters, residential furnaces, and solar equipment. Its purpose is to supply the energy needed by the fans, heating coils, cooling coils, or baseboards (simulated in the SYSTEMS program), and the electricity needed by the building's lights and office equipment (simulated in the LOADS program). Building loads can be satisfied by using the user-defined plant equipment or by the use of utilities; electricity, purchased steam, and/or chilled water.

The equipment is simulated in the following order:

1. The space heating loads are first reduced by energy supplied by the solar equipment.

2. Next, the hot and cold loop circulation pumps are simulated (if they exist). The heating and cooling loads are adjusted for any losses that occur in the circulation loops and for the addition of pump heat.

3. Then the chillers, cooling tower, and the cold storage tank are modeled. The chiller electrical load can then be added to the generator simulation (Step 5).

4. Generators, if specified, are used either for base electrical loads or for peak shaving.

5. Next, heat recovery equipment, if specified, is simulated to link the user-specified sources of waste heat to the user-specified heat demands.

6. Following heat recovery, boilers are simulated to satisfy any remaining heating loads.

7. Finally, the program allocates any remaining heating, cooling, and electrical loads to the appropriate utilities. If an utility is not allowed, the load is reported as an overload.

The order used will give accurate results for plants containing just boilers, chillers, towers, and storage tanks. Small discrepancies may result when simulating plants utilizing electric generators. This is because the electricity consumed by fossil boiler draft fans, electric boilers, and storage tank circulation pumps is calculated after the generators have already been simulated. These electrical loads are either passed on to the electrical utility, or, when simulating a total energy plant with no utility hookup, the loads are not satisfied and are reported as overloads.

1.2 Communication with Other Programs

The PLANT program reads files written by BDL and by SYSTEMS, and writes an output file to the ECONOMICS simulator. The file written by BDL (the "standard" file STDFIL), contains information specifying the types, number of and sizes of equipment, performance data, control strategies, and economic data. The user can learn about the information passed in the standard file by using the DIAGNOSTIC COMMENTS instruction in his BDL input.

The design file written by SYSTEMS (DSNFIL) is read at the beginning of the simulation. It contains:

1. Information about the RUN-PERIODs.

2. The names of PLANT equipment that SYSTEMS is directing output to.

3. Information for the BEPS report.

4. Peak heating, cooling, and electrical loads.

5. Ground temperatures, clearness numbers, and building location data for the solar simulator.

The SYSTEMS hourly output file, SYSOUT, contains the following information:

1. Domestic or process hot water loads.

2. Heating and cooling loads from system coils and baseboards. These loads do not include any loads met directly by packaged equipment simulated in SYSTEMS.

3. Electrical loads. Included is all electrical energy consumption from LOADS and SYSTEMS (lights, elevators, fans, electric resistance heating coils, electric loads from packaged equipment simulated in SYSTEMS, etc.).

4. Gas and fuel oil usage from LOADS and SYSTEMS. The usage includes fuel specified in the BUILDING-RESOURCE command as well as fuel consumed by packaged equipment simulated in SYSTEMS.

5. Flags that indicate whether or not heating and/or cooling is allowed in SYSTEMS (but not necessarily needed). These are used in conjunction with the BOILER-CONTROL and CHILLER-CONTROL = STANDBY keywords to force plant equipment to operate whenever it is scheduled to be on in SYSTEMS, even though there may be no load.

6. Dry-bulb and wet-bulb temperatures. The dry-bulb temperature is used in modeling chillers with air-cooled condensers and gas turbine generators. The wet-bulb temperature is used in modeling the cooling tower.

7. Information used by the solar simulator:

a. Preheat coil, main coil, zone coil, and baseboard heating loads (Note: the baseboard heating load is currently not used directly by solar).

b. Main coil and zone coil entering air temperature. The air entering the preheat coil is assumed to be at the outside dry-bulb temperature.

c. Preheat coil, main coil, and zone coil air flow rates.

The solar simulator uses the quantities listed here, in conjunction with the solar system temperatures, to calculate how much heat the solar system is able to supply.

At the end of the PLANT run, the PLANT program adds the following information to the design file (DSNFIL) for use in the ECONOMICS subprogram:

1. interest and escalation rates,
2. total first cost of all plant equipment,
3. total replacement costs for all plant equipment,
4. total site and source energy,
5. total energy costs for each year of the life-cycle period, and
6. total operations and maintenance costs for each year of the life-cycle period.

Finally, the PLANT program writes two report files: REPFIL for the output report generator and HRREP for the hourly report generator.

1.3 Simulation Limitations

1. There are several limitations that arise as a result of the flow of information between the subprograms. All of the information is communicated in one direction only. As a result, a subprogram "upstream" of the subprogram being simulated cannot make use of any information in the "downstream" program. For example, the heat extraction rates of the coils in SYSTEMS cannot be adjusted for any overloads that occur in PLANT. Because the coils in SYSTEMS thought they used the energy, the energy should be accounted for. This is accomplished later in PLANT by passing the overload from hour to hour until it is finally met. The coil overloads will not be passed from hour to hour indefinitely. If the overload has not been satisfied by the time heating or cooling is scheduled to be off, the overload is reported as a load not met. This rule applies to SYSTEM coil loads only. Any electrical load, domestic or process hot water load, or furnace load will not be passed to the next hour and the energy will not be accounted for, except as an overload. This problem is not very serious if the PLANT overload is a small percentage of the load. However, the user is cautioned not to undersize equipment by very much.

   The one-way flow of information also does not allow several building control strategies to be simulated. For example, the user might want to reduce his peak electrical load by turning out some lights during those hours when the electrical demand is high. Because the total electrical load is not calculated until the PLANT program is run, the lights in LOADS cannot be adjusted.

2. If multiple sizes of a given equipment type are operating simultaneously, the program models them as if all the sizes operating were lumped together into one large unit. The assumption here is that pieces of the same type of equipment will have identical performance curves regardless of size. Also, it is assumed that all pieces of the same type will be operating at the same fraction of their design capacity.

   For example, assume Boiler No. 1, a 4MBtu boiler, and Boiler No. 2, a 5MBtu boiler, are operating simultaneously to meet a heating load of 7MBtu. It is not possible to specify that Boiler No. 1 output is 4MBtu and Boiler No. 2 output is 3MBtu. Rather, each boiler will output 7/(5+4) of its design capacity. This would result in Boiler No. 1 output of (7/9)(4) or 3.1MBtu and Boiler No. 2 output of 3.9MBtu. This does not apply if they are different types of boilers, i.e., one a fossil-fueled boiler, the other an electric boiler.

3. Finally, as previously stated, electricity needed to operate a boiler or a storage tank pump is not accounted for in a total energy plant, i.e., a plant using generators to supply 100 percent of the electricity.

4. The PLANT subprogram does not make checks to see if the type equipment and fuel types the user has input are compatible. For example, steam heating systems are not compatible with hot water storage tanks, but if the user inputs this configuration, the program will simulate it. The energy flow in the program is in terms of Btus, and the program makes no effort to distinguish the type of energy being used.

In summary, it is up to the user to input reasonable data.

These limitations apply to the simulation as a whole. Additional rules that are specific to a given algorithm in the subprogram are listed in the description of that algorithm.

2. ALGORITHM DESCRIPTIONS

This section describes all the equipment and cost algorithms in the PLANT simulator (except for the solar equipment algorithms, which are described in Sec. 3 of this chapter). All calculations of energy are in Btus, including electrical energy and fossil fuels.

2.1 Use of Adjustment Curves in the Equipment Algorithms

Adjustment curves are used to correct the performance of a piece of equipment for off-design (off-rated) conditions. Off-design conditions may include operating at loads less than the design (rated) capacity, and/or operating at temperatures other than the design temperatures. In almost all of the equipment simulations, only one curve will be required in calculating the energy consumption at reduced (off-design) loads. Other curves may be required to adjust the energy consumption for off-design temperatures (as in the chiller simulations) or to predict other factors such as the fraction of fuel energy that is lost to the cooling jacket of a diesel engine.

Normally, it is not necessary for the user to specify the equipment performance curves. The program has within it default performance curves that will be used. However, the user may override the default curves by specifying his own performance curves (see the CURVE-FIT instruction in BDL, plus the PART-LOAD-RATIO and EQUIPMENT-QUAD instructions in PLANT). Although the specification of default-overriding performance data is done in the PLANT input, the calculation of the new performance curve is done in BDL. Those calculations are discussed in Chap. II of this manual.

This section is a general introduction to the way curves are used in the equipment algorithms. The user is cautioned to read the description of the applicable algorithm for specific details. The development here will be for equipment that uses fuel or heat as its energy source; however, electrically powered equipment is simulated in an identical fashion.

Variable List:

Keywords	FORTRAN Variables	Engineering Variables	Description
	CAP	CAP	The design (rated) capacity of the equipment corrected by the PLANT simulation for off-design conditions.
	CHWT	CHWT	The chilled water temperature leaving the chiller.
	ECT	ECT	The water temperature entering the chiller condenser.

Keywords	FORTRAN Variables	Engineering Variables	Description
[*]-EIR-FPLR	EIR2	EIR(PLR)	A function that describes the dependence of the electric input ratio, EIR, on the part load ratio, PLR.
ELEC-INPUT-RATIO	EIR(IEQTYP)	EIR_{des}	The electric input ratio of the equipment when operating at design (rated) capacity.
	FRAC	FRAC	The fraction of the hour when the chiller is cycled on.
[**]-HIR-FPLR	HIR2	HIR(PLR)	A function that describes the dependence of the heat input ratio, HIR, on the part load ratio, PLR.
[**]-HIR	HIRNOM	HIR_{des}	The heat input ratio of the equipment when operating at design (rated) capacity.
[**]-HIR-FT	HIR1	HIR-FT	A function describing the dependence of the HIR on the chilled water and condenser water temperature.
	LOAD	LOAD	The heating or cooling load required from the equipment this hour.
MIN-RATIO	RMIN	MIN-RATIO	The minimum fraction of design (rated) load at which the item of equipment can operate continually.
	PL	PLR	The part load ratio is the fraction of the equipment's design (rated) capacity needed this hour.

[*] can be replaced by the keyword OPEN-CENT, OPEN-REC, HERM-CENT, HERM-REC, or DBUN as appropriate.
[**] can be replaced by the keyword ABSOR1, ABSOR2, ABSORS, FURNACE, STM-BOILER, HW-BOILER, or DHW as appropriate.

2.1.1 Energy Consumption at Design Conditions

Energy consumption at design conditions is usually calculated as follows:

$$\text{Energy} = (\text{CAP}) * (\text{HIR}_{des}), \qquad (\text{V.1})$$

where CAP is the design (rated) capacity of the equipment and HIR_{des} is the heat input ratio ($\text{Btu}_{input}/\text{Btu}_{output}$), both at the design point. HIR_{des} is the inverse of the efficiency at the design point. HIR_{des} may be set by the user through the appropriate keywords, such as FURNACE-HIR, in the PLANT-PARAMETERS instruction.

2.1.2 Energy Consumption at Reduced (Part) Loads

The energy consumed at reduced loads is a function of the part load ratio (PLR), which is defined as

$$\text{PLR} = \text{LOAD/CAP},$$

where LOAD is the output of the machine needed this hour, and CAP is the design (rated) capacity of the machine, corrected for off-design conditions. The PLR is the fraction of the capacity needed. Equation (V.1) is modified as a function of the part load ratio as follows:

$$\text{Energy} = (\text{CAP}) * (\text{HIR}_{des}) * [\text{HIR(PLR)}]. \qquad (\text{V.1a})$$

HIR(PLR), the heat input ratio correction factor, is the fraction of the design energy consumption consumed at part load. By definition,

$$\text{HIR(PLR)} = 1.0.$$

The function HIR(PLR) is illustrated in Fig. V.1. If the efficiency of the machine is independent of the load, HIR(PLR) will be linear and pass through the origin (0 at 0 load). This is illustrated by the dashed curve. If the machine is most efficient at its rated capacity and becomes less efficient at lower part load ratios, the curve will be of the form shown by curve "a". If the machine is most efficient somewhere in the middle of the part load range, the curve will look something like curve "b". HIR(PLR) may be set by the user through the appropriate keyword, such as FURNACE-HIR-FPLR, in the EQUIPMENT-QUAD instruction. It is expressed mathametically as a polynomial, usually of second order,

$$\text{HIR(PLR)} = A + (B * \text{PLR}) + (C * \text{PLR}^2).$$

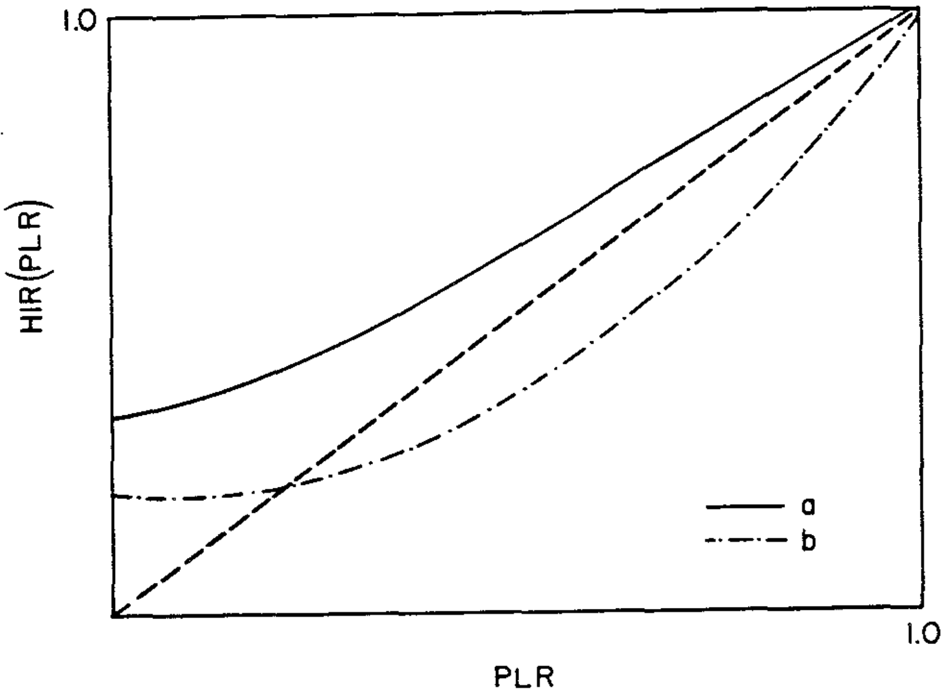


Fig. V.1. Heat input ratio vs. part load ratio for various equipment efficiency curves.

Equipment powered by electricity is simulated in an analogous manner:

$$\text{Energy} = (\text{CAP}) * (\text{EIR}_{des}) * [\text{EIR(PLR)}], \qquad \text{(V.1b)}$$

where EIR_{des} is the design electric input ratio. EIR_{des} can be input through the keyword ELEC-INPUT-RATIO in the PART-LOAD-RATIO instruction.

Some of the algorithms, such as in the diesel and gas turbine routines, use the more conventional energy consumption formula:

$$\text{Energy} = \text{LOAD}/[\text{eff(PLR)}] \; . \; . \; . \; . \qquad \text{(V.2)}$$

where eff(PLR) is the efficiency as a function of PLR and is illustrated in Fig. V.2.

This type of curve cannot be accurately fit with a low order (cubic or less) polynominal equation and, as a result, the algorithms are not very accurate at low part loads.

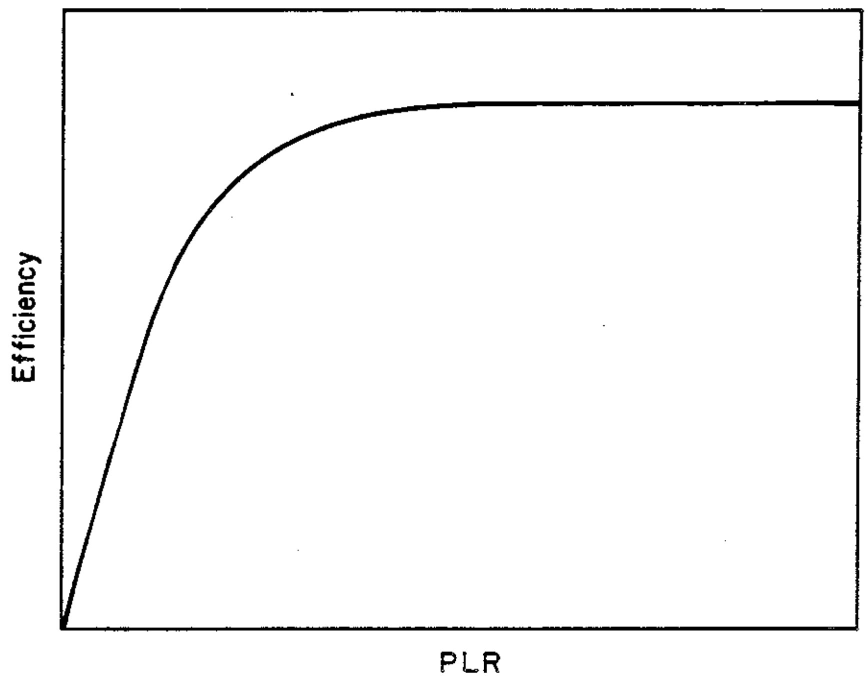


Fig. V.2. Typical equipment efficiency vs. part load ratio.

2.1.3 Operation Below the Minimum Part Load Ratio

The program simulates the operation of equipment below its minimum part load ratio (MIN-RATIO) differently, depending upon the type of equipment. Diesel and gas turbine generators are simply not operated at very low loads. Boilers and chillers are cycled on and off. During the time the equipment is cycled on, it is assumed to operate at the minimum part load ratio.

The calculation of energy consumed when cycling varies. For all types of heating equipment and absorption chillers, the cycling is taken into account in the curves for part load performance. For compression chillers, the fraction of the hour the chiller is cycled on is multiplied by the energy consumed at non-cycling operation at the minimum part load ratio

$$\text{Energy} = (\text{CAP}) * (\text{EIR}_{des}) * [\text{EIR(MIN-RATIO)}] * (\text{FRAC}),$$

where FRAC is calculated as:

$$\text{FRAC} = \frac{\text{PLR}}{\text{MIN-RATIO}} .$$

Compression chillers are modeled differently when cycling because of false loading effects. See the equipment algorithms for more details.

2.1.4. Effect of Temperature on Energy Consumption

The energy consumption of some types of equipment, notably chillers, is dependent on temperatures as well as the part load ratio. For chillers, the energy consumption is usually dependent on both the entering condenser water temperature (ECT) and the leaving chilled water temperature (CHWT). Equation (V.1) is modified to take the temperature into account as follows:

$$\text{Energy} = (\text{CAP}) * (\text{HIR}_{des}) * [\text{HIR(PLR)}] * [\text{HIR-FT(CHWT, ECT)}],$$

where HIR-FT(CHWT,ECT) is a bi-quadratic function of the water temperatures that can be input using the appropriate EQUIPMENT-QUAD keyword. Expressed in this form, the temperature term adjusts the energy used at a given part load ratio by a constant percentage, as shown in Fig. V.3.

One study (Ref. 1) has indicated that the temperature effects are not important at lower part load ratios. This effect has not been modeled in the present code.

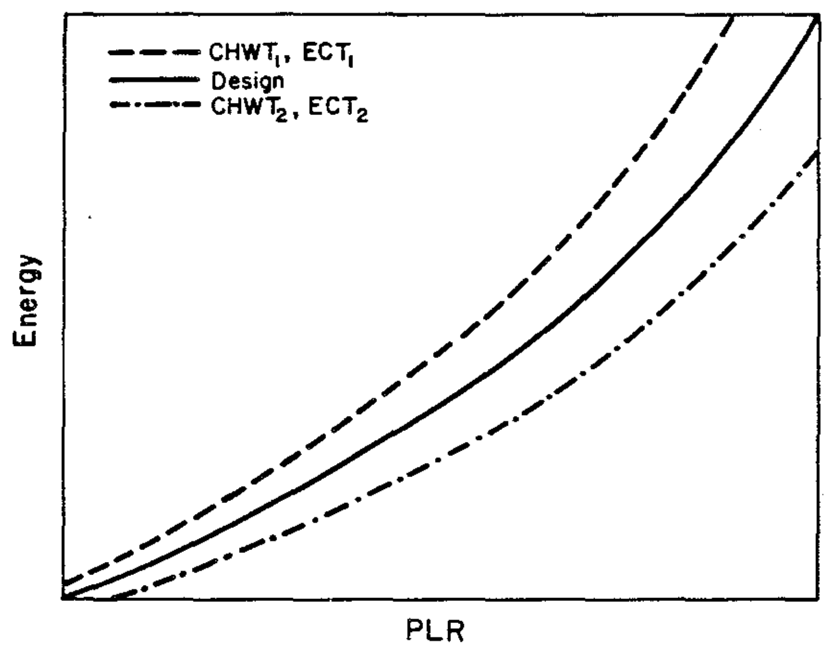


Fig. V.3. Effect of water temperature on chiller energy consumption.

2.2 Equipment Algorithms

This section describes the algorithms that are used in the PLANT simulation. The algorithms are grouped by function or similarity rather than alphabetically. In cases where some of the algorithms are almost identical to others, only one of the algorithms will be discussed in detail. The others will be described in terms of their differences.

Some of the algorithms require that some design calculations be done at the beginning of simulation. With the exception of the variables calculated in subroutine DEFALT, which is discussed immediately below, the design calculations are discussed in conjunction with the algorithms in which they are used.

2.2.1 General Design Calculations (subroutine DEFALT)

Subroutine DEFALT calculates the variables that are used generally in other algorithms.

Variable List:

Keywords	FORTRAN Variables	Engineering Variables	Description
	CLSUM	CLSUM	The design cooling load calculated by the SYSTEMS simulation.
	ELSUM	ELSUM	The peak electrical load calculated by the SYSTEMS simulation.
	HSTURB	HSTURB	The steam-turbine enthalpy.
	HTSUM	HTSUM	The design heating load calculated by the SYSTEMS simulation.
STM-PRES	PSTEAM	PSTEAM	The boiler steam pressure.
STURB-PRES	PSTURB	PSTURB	The steam pressure entering a steam-turbine generator.
see REFERENCE-COST command		Reference Cost	Cost parameters for equipment of the reference size.
SIZE		SIZE	The equipment design (rated) capacity.
SIZE-REF		SIZE-REF	The capacity of equipment used as a reference for cost calculations.

Keywords	FORTRAN Variables	Engineering Variables	Description
	TOTCAP	TOTCAP	The total design (rated) capacity of each equipment type (summed over all sizes of a given type).
STM-SATURATION-T	TSATUR	TSATUR	The steam saturation temperature.
STURB-T	TSTURB	TSTURB	The temperature of steam entering the steam-turbine generator.
MAX-NUMBER-AVAIL	KAV	KAV	The number of units of each equipment type.

Description of Calculations

1. Precedence rule -

   The first variables calculated in this routine are those associated with the "precedence rule" discussed under the PLANT-EQUIPMENT command in the DOE-2 Reference Manual (Ref. 2). Briefly, this rule states that, unless the user allocates equipment loads through the use of the LOAD-ASSIGNMENT and the LOAD-MANAGEMENT commands, only one type of boiler, compression chiller, absorption chiller, and cooling tower will be allowed to operate. This rule does not apply to different sizes of the same equipment type.

   For example, two different sizes of fossil fuel steam boilers can be input without making use of a LOAD-ASSIGNMENT and the program will operate them by default with no difficulty. However, if an electric steam boiler is input in addition to a fossil fuel steam boiler, only the fossil fuel steam boiler will operate. The reason is that the default allocation algorithms are not general enough to allow more than one type in each equipment category. This is not a serious problem, because it is not very likely that an electric steam boiler would be used in the same plant as a fossil fuel steam boiler. However, if such a combination is to be used, the user must input a LOAD-ASSIGNMENT to instruct the program how they are to be used.

2. Steam data -

   The steam pressure, temperature, enthalpy and entropy are used in the steam turbine algorithm. The steam saturation temperature is used in the diesel engine and gas turbine generator routines to calculate the heat recoverable from the exhaust gases.

   a. Steam pressure (FORTRAN variable PSTEAM or PSTURB for steam-turbines) -

If the steam pressure is not input using the STM-PRES keyword, the steam pressure is normally defaulted to 15 psig. For a two-stage absorption chiller or a steam turbine, the steam pressure will default to 150 psig. Finally, if the user inputs a value for the steam-turbine pressure by using the keyword STURB-PRES, the pressure must be at least the default value.

b. Steam saturation temperature (FORTRAN variable TSATUR) -

The steam saturation temperature is either user-defined through keyword STM-SATURATION-T or is calculated as a function of the steam pressure:

$$\mathrm{TSATUR} = \frac{1}{.0017887 - [.00011429 * \ln(\mathrm{PSTEAM} + 14.7)]} - 460 \text{ (Ref. 2).}$$

c. Steam turbine enthalpy (FORTRAN variable HSTURB) -

The entering steam-turbine temperature (FORTRAN variable TSTURB) for enthalpy calculation is either user-defined by keyword STURB-T or it will default to TSATUR + 125°F. The enthalpy is then calculated in subroutine ENTHAL as:

$$\begin{aligned}\mathrm{HSTURB} = {} & [1068.0 - 0.485(\mathrm{PSTURB} + 14.7)] \\ & + [0.432 + .000953(\mathrm{PSTURB} + 14.7)]\mathrm{TSTURB} \\ & + [0.000036 + (0.496 * 10^{-6})(\mathrm{PSTURB} + 14.7)]\mathrm{TSTURB}^2 \text{ (Ref.2).}\end{aligned}$$

d. Steam turbine entropy (FORTRAN variable SSTURB)

The steam turbine enthropy is calculated in subroutine ENTROP as:

$$\begin{aligned}\mathrm{SSTURB} = 2.385 & - (0.4398 * 10^{-2})\mathrm{TSATUR} \\ & + (0.8146 * 10^{-5})\mathrm{TSATUR}^2 \\ & - (0.626 * 10^{-8})\mathrm{TSATUR}^3 \\ & + 2C(\mathrm{TSTURB} - \mathrm{TSATUR}) + (B - 920C)\ln\left(\frac{\mathrm{TSTURB} + 460}{\mathrm{TSATUR} + 460}\right)\end{aligned}$$

where $B = 0.432 - (0.953 * 10^{-3}\ \mathrm{PSTURB})$
$C = (0.36 * 10^{-4}) - (0.496 * 10^{-6}\ \mathrm{PSTURB})$ (Ref. 2).

3. Total capacity of equipment type (FORTRAN variable TOTCAP) -

The total capacity of each equipment type is set equal to the sum of the design capacities of all equipment of that type. If the installed capacity is greater than the capacity available all at once (see keyword MAX-NUMBER-AVAIL), TOTCAP is set equal to the available capacity. TOTCAP is used in many of the equipment routines as well as the default load allocation routines.

4. Automatic sizing of all equipment defined by the user, but not sized by the user.

   a. Chillers -

      Chillers are sized by the program based on the design cooling load (FORTRAN variable CLSUM) specified by SYSTEMS. This load is adjusted for the circulation loop heat conduction and pump heat. The actual size of the chiller is the above quantity divided by the number of units input by the MAX-NUMBER-AVAIL keyword. If MAX-NUMBER-AVAIL is not defined, it is defaulted to 1.

   b. Boilers -

      Boilers are sized by the program in a manner similar to chillers, except that the heat needed by absorption chillers is taken into account. Additionally, if a furnace is defined, no circulation loop loss or pump energy is included. Also, if no domestic water heater is defined, the boiler sizing will take into account the domestic hot water load.

   c. Furnace -

      A furnace is sized by the program strictly upon the design heating load passed from the SYSTEMS simulation (HTSUM). No losses are included.

   d. Water heater -

      A domestic hot water heater is sized by the program based on the peak domestic/process water load incurred in the LOADS simulation.

   e. Turbine generators (diesel and gas) -

      The diesel and gas turbine generators are sized by the program based on the peak electrical load passed from the SYSTEMS simulation (ELSUM) plus the maximum possible electrical load in the PLANT simulation. The assumption is that all the equipment in PLANT may be simultaneously operating at maximum capacity at the same time that the peak electrical load in SYSTEMS occurs. It also assumes that the electrical equipment will be used to meet the entire electrical load, with no utility backup. Because neither of these assumptions is very likely, the user should probably not allow the program to size the generators.

   f. Steam turbines -

      The steam turbine generators are never automatically sized by the program. The steam turbine modeled by DOE-2 is only about 5 to 6 percent efficient and would normally only be used to take advantage of some waste steam or possibly as a backup electrical supply in a hospital.

5. Report scaling factor -

   The total anticipated electrical load, described in 4e above, is also used as the scaling factor in summary report PS-G.

6. Default equipment costs -

   If the user did not specify the equipment costs under the PLANT-EQUIPMENT command (FIRST-COST, INSTALLATION, etc.), the program will default the costs not so specified. The formula used is

$$\text{Cost} = (\text{Reference Cost}) * \left(\frac{\text{SIZE}}{\text{SIZE-REF}}\right)^{X} ,$$

   where the reference costs and the size of the reference equipment (SIZE-REF) are defaulted, or can be explicitly stated in the REFERENCE-COSTS command. X is a power that varies depending on which cost is being calculated (see Ref. 2). SIZE is the size of the equipment being costed.

7. Finally, subroutine DEFALT precalculates some variables for the double bundle chiller simulation. These variables are presented in the section on the DBUNDL subroutine.

2.2.2 Heating Equipment

The PLANT simulation is capable of calculating fuel consumption and operating costs for fossil fuel steam and hot water boilers, electric steam and hot water boilers, electric and fossil fuel domestic/process water heaters, and a fossil fuel furnace. The boiler(s) will normally operate only when there is a heating load. If the user inputs BOILER-CONTROL = STANDBY, the boiler(s) will operate at all times that heating is scheduled to be on in SYSTEMS, even if there is no heating load. All of the fossil fired heating equipment algorithms are almost identical and are discussed together. The same applies to the electrical heating equipment.

Variable List:

Keywords	FORTRAN Variables	Engineering Variables	Description
	CAPOP	CAPOP	The sum of the design (rated) capacities of all fossil fuel heating equipment of a given type operating this hour.
ELEC-INPUT-RATIO	EIR	EIR	The electric input ratio.

Keywords	FORTRAN Variables	Engineering Variables	Description
	FBLOW	FBLOW	The amount (lbs) of water that must be periodically blown down from a steam boiler.
	FRAC	FRAC	The fraction of the hour a boiler actually operates.
	FSLOSS	FSLOSS	The lbs of steam lost from the steam boiler during a blowdown.
	FUEL	FUEL	The fuel consumption.
	FWMAKE	FWMAKE	The makeup water needed after a boiler blowdown.
STM-BOILER-HIR HW-BOILER-HIR	HIRB	HIRB	The fuel (heat) input ratio at the design (rated) boiler capacity.
[*]-HIR-FPLR	HIRCOR	HIRCOR	The fuel (heat) input correction factor as a function of part load ratio (linear, quadratic, or cubic equation).
DHW-HIR	HIRDHW	HIRDHW	The fuel (heat) input ratio at the design (rated) hot water heater capacity.
FURNACE-HIR	HIRF	HIRF	The fuel (heat) input ratio at the design (rated) capacity of the furnace.
	HTAVAL	$HTAVAL_i$	The heat that is recoverable from a steam boiler blowdown.
	HTREQD	$HTREQD_i$	The energy needed to heat the makeup water required after a steam boiler blowdown.
	LOAD	LOAD	The demand on the boiler this hour.
		LOSS	The skin losses from the equipment operating this hour.

[*] = STM-BOILER, HW-BOILER, FURNACE or DHW as appropriate.

Keywords	FORTRAN Variables	Engineering Variables	Description
E-STM-BOILER-LOSS E-HW-BOILER-LOSS		LOSSES	The fraction of the design (rated) boiler capacity lost through the skin.
		OPCAP	The sum of the design (rated) capacities of all electrical heating equipment operating this hour.
	PLR	PLR	The part load ratio is the fraction of the equipment's design (rated) capacity needed this hour.
	PILOT	PILOT	The fuel consumption of a furnace pilot light this hour.
BOILER-BLOW-RAT		RBLOW	The boiler blowdown flow rate as a fraction of steam losses from a steam boiler (i.e., steam entering the turbine less the condensate returned to the feedwater system divided by the total steam lost).
RECVR-HEAT/BLOW		RHBLOW	The effectiveness of blowdown heat recovery.
MIN-RATIO		RMIN	The minimum fraction of the design (rated) load at which the item of equipment can operate continually.
STM-SATURATION-T	TSATUR	TSATUR	The steam saturation temperature.
MAKEUP-WATER-T	TWMAKE	TWMAKE	The temperature of steam boiler makeup water.

2.2.2.1 Fossil Fuel Heating Equipment (subroutines BOILER, FURNAC, and GASDHW)

Subroutine BOILER simulates the fossil fuel steam boiler (STM-BOILER) and fossil fuel hot water boiler (HW-BOILER). Subroutine FURNAC simulates the furnace (FURNACE) and GASDHW simulates the gas domestic hot water heater (DHW-HEATER). All of these routines have identical calculations for fuel consumption, with the exception of the pilot light calculation for the furnace. The major difference between these algorithms is in the calculation for electricity. Subroutine BOILER will be presented here in detail, and the differences in the other two algorithms will be explained.

2.2.2.1.1 Steam or Hot-Water Boiler (subroutine BOILER)

The simulation input/output can be illustrated as in Fig. V.4.

Fuel consumption - The fuel consumption is calculated in the manner presented in Sec. V.2.1. The part load ratio (FORTRAN variable PLR) is

$$PLR = \frac{LOAD}{CAPOP},$$

where LOAD is the demand on the boiler(s) this hour and CAPOP is the sum of the design (rated) boiler sizes operating this hour. The heat input ratio (FORTRAN variable HIRCOR) is:

$$HIRCOR = f_1(PLR),$$

where $f_1()$ is a quadratic equation whose terms describe the dependence of the heat input ratio on the PLR. f_1 can be input through the keywords STM-BOILER-HIR-FPLR or HW-BOILER-HIR-FPLR, depending on whether the steam or hot water boiler is being simulated.

The fuel consumed is

$$FUEL = CAPOP * HIRB * HIRCOR,$$

where HIRB is the design (rated) capacity fuel input ratio. HIRB is input by keywords STM-BOILER-HIR or HW-BOILER-HIR. For the case when the part load ratio is lower than the minimum part load ratio (FORTRAN variable RMIN), the boiler is assumed to cycle on and off. The fuel consumption can still be calculated using the above formula. The electrical consumption, however, will be affected as follows.

Electrical consumption - The fraction of the hour the boiler is actually operating is

$$FRAC = \frac{PLR}{RMIN} \text{ or } 1.0, \text{ whichever is smaller,}$$

where RMIN is the minimum part load ratio and can be input using the keyword MIN-RATIO. Note that FRAC $\geq$ 1.0 corresponds to continuous boiler operation.

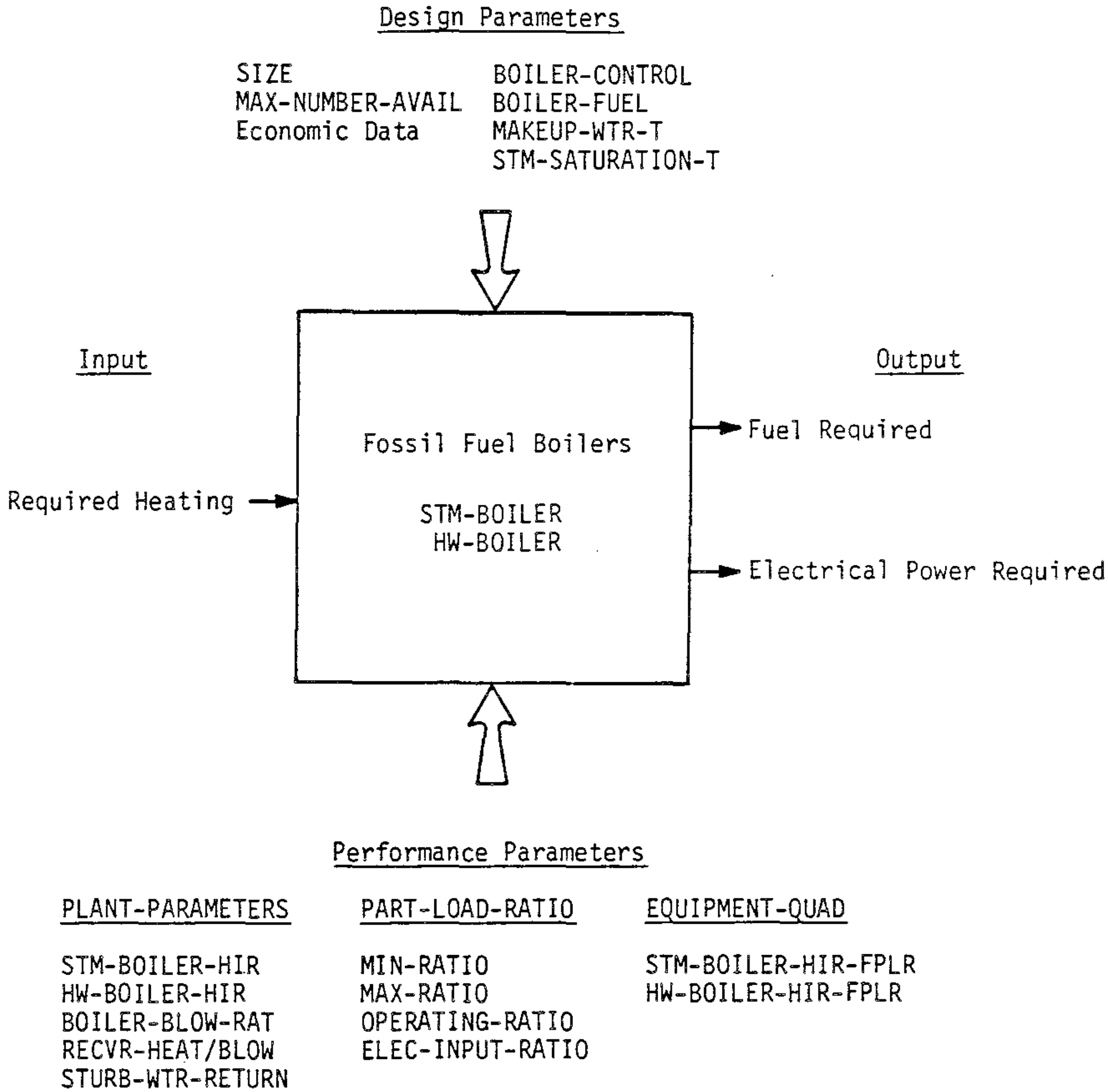


Fig. V.4. Fossil fuel boiler simulation.

The electricity consumed is:

ELEC = CAPOP * EIR * FRAC,

where EIR is the electric input ratio that can be input by the keyword ELEC-INPUT-RATIO.

This calculation assumes that the electrical consumption is constant, provided the boiler is not cycling. The electricity is assumed to be needed for draft fans, fuel pumps, stokers, etc. For a natural draft gas fired boiler, the electric input ratio = 0.

Recoverable heat (steam boiler only) - When using a steam boiler (STM-BOILER), it is normally assumed that all of the steam produced is returned to the boiler as condensate. The exception is when a steam turbine generator is being utilized. In this case, only a fraction of the steam used by the turbine is returned as condensate (specified by keyword STURB-WTR-RETURN). The steam boiler must be blown down periodically to prevent mineral salts from building up and fouling the heat exchanger. A small amount of heat can be recovered from the blowdown and a small amount is needed to heat the feedwater. These calculations are done in subroutine PIPES. They apply only to the steam boiler.

The amount of water that must be blown down (lbs) is

$$FBLOW = FSLOSS * RBLOW,$$

where FSLOSS is the pounds of steam lost from the steam turbine, and RBLOW is the blowdown ratio and corresponds to the keyword BOILER-BLOW-RAT.

The makeup water needed is the sum of the loss and the blowdown

$$FWMAKE = FSLOSS + FBLOW.$$

The energy needed to heat the makeup water to the steam saturation temperature is

$$HTREQD_i = FWMAKE * (TSATUR - TWMAKE),$$

where TSATUR, the steam saturation temperature, corresponds to the value input, or defaulted, for the keyword STM-SATURATION-T. TWMAKE, the makeup water temperature, corresponds to the keyword value for MAKEUP-WATER-T. $HTREQD_i$ can be specified as a demand in the HEAT-RECOVERY command through the codeword STM-BOILER.

The heat that is recoverable from the blowdown is equal to the energy in the blowdown multiplied by the recoverable heat ratio (RHBLOW)

$$HTAVAL_i = FBLOW * (TSATUR - TWMAKE) * RHBLOW.$$

RHBLOW is the effectiveness of blowdown heat recovery and corresponds to the keyword RECVR-HEAT/BLOW. Note that the recoverable heat is referenced to the makeup water temperature. It is assumed here that this heat will only be used to heat the makeup water ($HTREQD_i$, calculated above). $HTAVAL_i$ can be specified as a supply in the HEAT-RECOVERY command through the codeword STM-BOILER.

2.2.2.1.2 Gas Furnace (subroutine FURNAC)

The simulation input/output can be illustrated as in Fig. V.5.

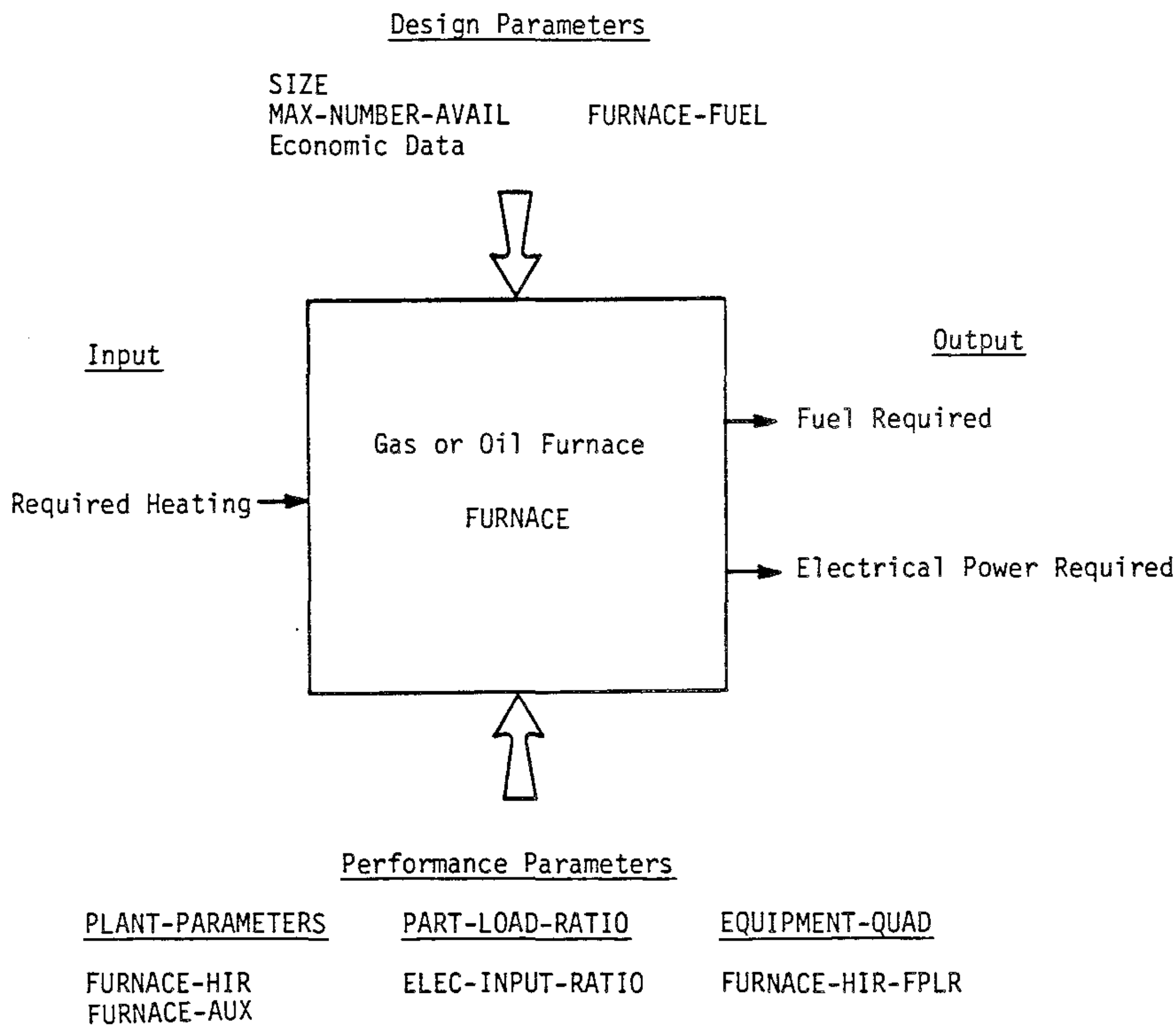


Fig. V.5. Gas or oil furnace simulation.

The fuel consumption during the hours the furnace is operating is the same as for the fossil fuel boilers

FUEL = CAPOP * HIRF * HIRCOR,

where HIRF is the fuel input ratio at design (rated) load (input through keyword (FURNACE-HIR). HIRCOR is calculated from the part load ratio curve input by keyword FURNACE-HIR-FPLR.

During the hours the furnace does not operate at all, the fuel consumption is simply

FUEL = PILOT,

where PILOT is the fuel consumption of the furnace pilot light and corresponds to the keyword FURNACE-AUX. This is to take into account any fuel consumption from a pilot light. If an electronic ignition device is used in place of a pilot, keyword FURNACE-AUX should be set to 0.

The electricity consumed is

ELEC = CAPOP * EIR * PLR.

Here the part load ratio, PLR, is used because it is assumed that furnace does not have any means of capacity reduction other than cycling on and off. In this case, PLR is equal to the fraction of the hour the furnace is operating.

2.2.2.1.3 Gas Domestic Hot-Water Heater (subroutine GASDHW)

The simulation input/output can be illustrated as in Fig. V.6.

The fuel consumption is calculated the same as for the fossil boilers

FUEL = CAPOP * HIRDHW * HIRCOR,

where HIRDHW is the fuel input ratio at design (rated) capacity (input through keyword DHW-HIR). HIRCOR is a function of the part load ratio and is calculated from the curve input by keyword DHW-HIR-FPLR. HIRCOR is valid for all part load ratios where $0 \leq$ PLR $\leq$ MAX-RATIO.

The electricity consumption is

ELEC = CAPOP * EIR.

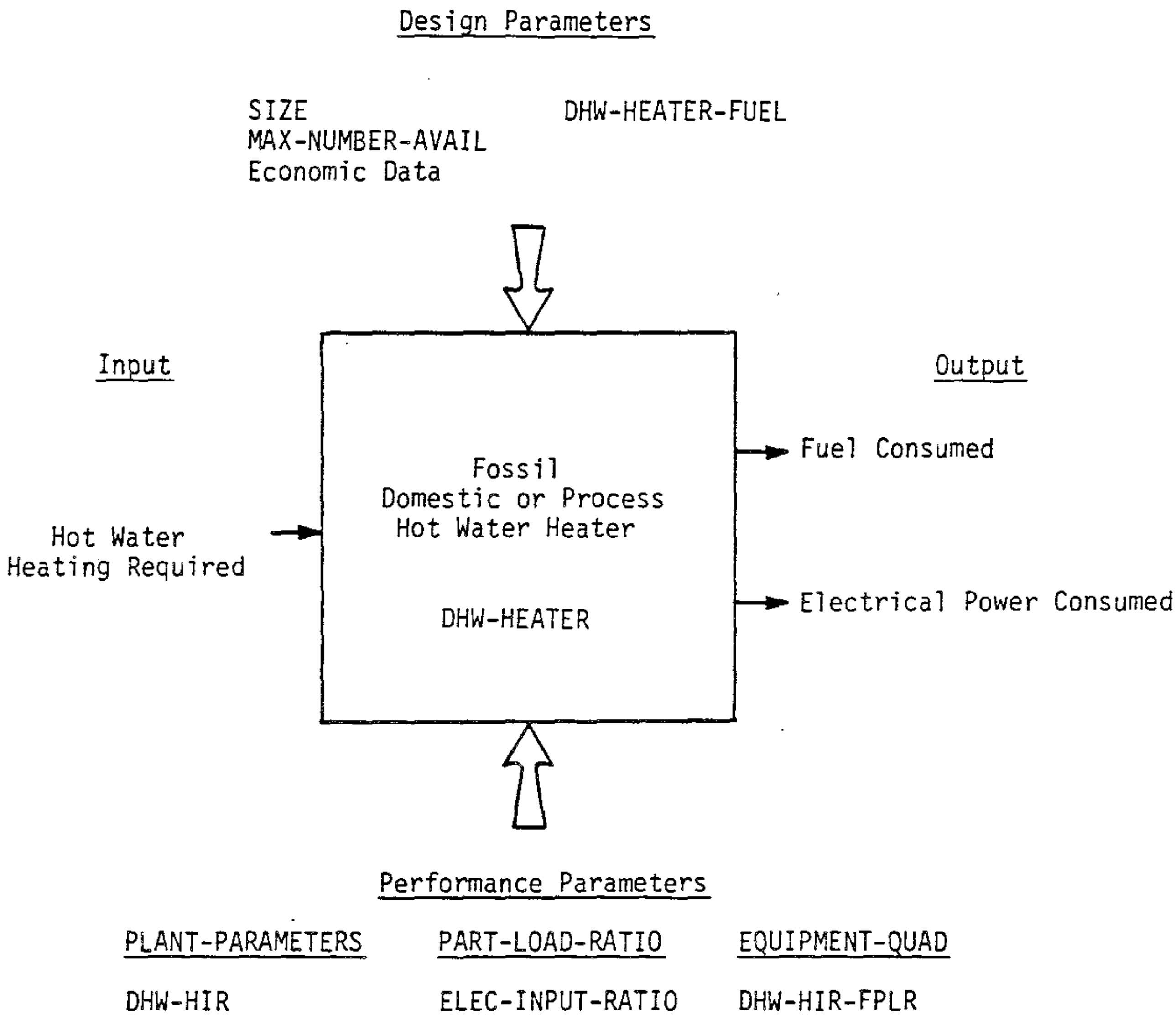


Fig. V.6. Hot water heater simulation.

In this algorithm, the electrical consumption is constant regardless of the load. The assumption is that the electricity is used by a water circulation pump that runs constantly. Note that the default for keyword ELEC-INPUT-RATIO is 0 for the DHW-HEATER.

2.2.2.2 Electric Boilers and Heaters (subroutines ELBOIL and ELDHW)

The simulation input/output can be illustrated as in Fig. V.7.

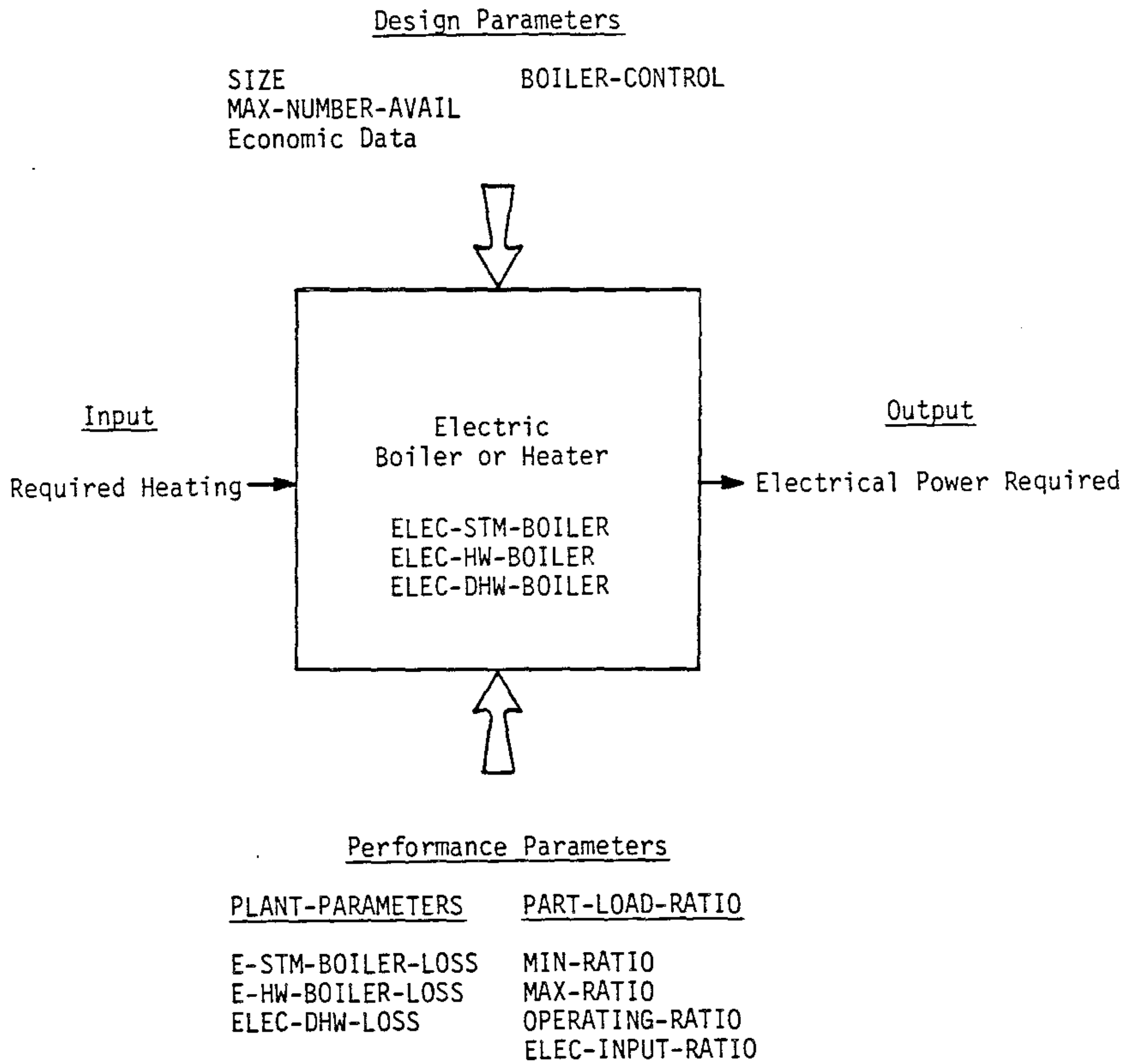


Fig. V.7. Electric heating equipment simulation.

Electricity consumption for the electric steam boilers, electric hot water boilers and electric domestic hot water heaters is modeled identically. The hot water heater is in a separate algorithm because it is assumed to be operating all hours even when there is no load. The algorithm for electrical heating equipment assumes that there is a constant skin loss, regardless of load. In addition, there can be an additional loss that is proportional to the power consumed. This loss would be from resistance heating in the electrical leads supplying power to the boiler.

The skin losses from the boiler are

LOSS = LOSSES * OPCAP

where LOSSES is the fraction of the rated capacity lost through the skin and the keyword E-STM-BOILER-LOSS, E-HW-BOILER-LOSS or ELEC-DHW-LOSS, depending on the type being simulated. OPCAP is the sum of the rated capacities of all of this type of equipment that are operating this hour. For the electric hot water heater only, OPCAP is always the capacity of the maximum number of heaters that can run in one hour. For the electric boilers, OPCAP can vary depending on how many units are needed to meet the load.

The energy consumed is

ELEC = (LOAD + LOSS) * EIR,

where LOAD is the heating load on the equipment and EIR is the electrical input ratio and corresponds to the keyword ELEC-INPUT-RATIO. The defaults for the EIR for all types of electrical heating equipment is 1.0. Setting EIR > 1.0 will approximate the resistance heating in the electrical leads supplying power to the boiler. Note that in reality the resistance heating losses would increase in proportion to the square of the current. In this mode, it is linear.

2.2.3 Cooling Equipment

2.2.3.1 General

The PLANT simulator is capable of modeling a variety of central water chillers. Direct expansion air-conditioning units are modeled in the SYSTEMS simulator.

One- and two-stage absorption chillers are modeled in subroutine ABSREF. Centrifugal and reciprocating chillers (both open and hermetic) are modeled in subroutine COMREF. Double bundle heat recovery chillers are modeled in subroutine DBUNDL. A conventional or ceramic cooling tower (subroutine TOWER) is simulated for chillers having water-cooled condensers. In addition to simulating conventional operation, two different modes of using the cooling tower for direct cooling are also modeled. The first mode (code-word STRAINER-CYCLE), models cooling tower water passing directly into the chilled water loop. In the second mode (code-word THERMO-CYCLE), the compression chiller is modeled as a heat exchanger. Air-cooled condensers are optional for the chillers in COMREF.

The chiller(s) will normally operate only when there is a cooling coil load from SYSTEMS, or when the chilled water storage tank is charging. If the user inputs the option CHILLER-CONTROL = STANDBY, the chiller(s) will operate at all times that cooling is scheduled on in SYSTEMS, even if there is no cooling load. All of the chiller algorithms assume that the performance of the chillers, both capacity and energy consumption, will vary with the chilled water temperature, CHWT, and with the entering condenser water temperature, ECT. The energy consumption is also a function of the load on the machine.

Variable List:

Note: The following variables are those used in the chiller simulations only. The cooling tower portion of this section contains a separate variable list.

Keyword	FORTRAN Variables	Engineering Variables	Description
	ALOAD	ALOAD	The demand on a compression chiller exclusive of any false loading.
	CAP	CAP	The available capacity of a chiller (adjusted for off-design water temperature).
	CHWT	CHWT	The temperature of chilled water.
	CLSUM	CLSUM	The peak cooling load incurred in the SYSTEMS simulation.
DBUN-TO-TWR-WTR	DBWTR	DBWTR	The water flow rate to the cooling tower for a double bundle chiller. (GPM/ton)
	ECT	ECT	The entering condenser water temperature.
OPEN-CENT-MOTOR-EFF OPEN-REC-MOTOR-EFF	EFFMOT	$EFFMOT_i$	The fraction of the chiller compression electrical input energy that is converted to shaft energy.
ELEC-INPUT-RATIO	EIR	EIR_i	The electic input ratio = electric power input/design capacity of equipment.
	EIR1	EIR1	The power correction factor for off-design temperature.
	EIR2	EIR2	The power correction factor for part load ratio.
	ELEC	ELEC	The electrical energy required.

Keyword	FORTRAN Variables	Engineering Variables	Description
ABSOR[*]-HIR-FT	HIRT	f_1	A bi-quadratic expression for the heat input ratio temperature correction factor.
ABSOR[*]-HIR-FPLR	HIRPLR	f_2	A cubic expression for the heat input ratio correction factor for part load ratio.
ABSORS-HIR-FTS	HIRTS	f_3	A quadratic expression for the heat input ratio correction factor for varying solar supply temperature.
[**]-EIR-FT	EIRT	f_4	A bi-quadratic expression for the power correction factor for off-design temperatures.
[**]-EIR-FPLR	EIRPLR	f_5	A quadratic expression for the power correction factor for part load ratio.
DBUN-EIR-FTRISE	EIRREC	f_6	A quadratic expression for the heat recovery power adjustment factor as a function of the rise in condensing temperature when in the heat recovery mode.
[***]-CAP-FT	ACAPT ACAPTS DBCAPT CCAPT	f_7	A bi-quadratic expression for the capacity adjustment factor for off-design temperatures.
ABSORS-CAP-FTS	ACAPTS	f_8	A quadratic expression for the capacity adjustment factor for varying solar supply temperature.
	FALSLD	FALSLD	The false loading of a compression chiller caused by a low part load ratio.
	FANE	FANE	The condenser fan electrical energy for air-cooled condenser.
[*]-COND-PWR	$FANELC_i$	$FANELC_i$	The condenser fan electric ratio.

[*] can be replaced by ABSOR1, ABSOR2, or ABSORS, as appropriate.
[**] can be replaced by HERM-CENT, HERM-REC, OPEN-CENT, OPEN-REC, or DBUN as appropriate.
[***] can be replaced by ABSOR1, ABSOR2, ABSORS, HERM-CENT, HERM-REC, OPEN-CENT, OPEN-REC, or DBUN, as appropriate.

Keyword	FORTRAN Variables	Engineering Variables	Description
	FRAC	FRAC	The fraction of the hour the chiller is operating.
	HEAT	HEAT	The heat energy consumed by an absorption chiller.
	HIR1	HIR1	The heat input ratio temperature correction factor.
	HIR2	HIR2	The heat input ratio correction factor for part load operation.
ABSORS-HIR ABSOR1-HIR ABSOR2-HIR	HIRNOM	$HIRNOM_i$	The heat input ratio of the absorption chiller at design (rated) capacity.
	HIRS	HIRS	The heat input ratio correction factor for varying solar supply temperature.
	HTREC	HTREC	The amount of recoverable heat.
	LOAD	LOAD	The load this hour on this type of chiller.
	OPCAP	$OPCAP_i$	The sum of the design (rated) capacities of this type of chiller that are operating this hour.
	PDEM	$PDEM_2$	The hourly cooling load calculated in the SYSTEMS simulation.
	PL	PL	The average part load ratio over the hour.
	PLR	PLR	The part load ratio for a compression chiller. This term must be at least the minimum unloading ratio (see $RUNLD_i$).
	RCAP	$RCAP_i$	The capacity adjustment factor for off-design temperatures.
DBUN-CAP-COR-REC	RCREC	RCREC	The heat recovery capacity adjustment factor.
DBUN-EIR-COR-REC	RKWREC	RKWREC	The heat recovery power adjustment factor.

Keyword	FORTRAN Variables	Engineering Variables	Description
MIN-RATIO	RMIN	RMIN	The minimum part load ratio is the minimum fraction of rated load at which the chiller can operate continually.
DBUN-HT-REC-RAT	RRECVR	RRECVR	The ratio of the recoverable heat to the total heat rejection at full load.
[**]-UNL-RAT	RUNLD	$RUNLD_i$	The maximum part load ratio of a chiller at which hot gas bypass occurs.
	TAIR	TAIR	The outside dry-bulb temperature.
CHILL-WTR-T	TCOOL	TCOOL	The chilled water temperature at the middle of the throttling range.
DBUN-CON-T-ENT	TDES	TDES	The entering condenser temperature in non-heat recovery mode at the design point.
	TOUT	$T_{exit-des}$	The design exit temperature from the condenser.
CHILL-WTR-THROTTLE	THROTL	THROTL	The throttling range of the temperature controller.
	TOWER	TOWER	The total heat rejection to the cooling tower.
DBUN-COND-T-REC	TREC	TREC	The leaving condenser temperature in the heat recovery mode.
	TRISE	TRISE	The difference between the temperature of the leaving condenser water in the heat recovery mode and the leaving condenser water temperature at design conditions.
	TSOLAR	TSOLAR	The hot water supply temperature (solar system).
	TTOWR	TTOWR	The leaving cooling tower water temperature.

[**] can be replaced by HERM-CENT, HERM-REC, OPEN-CENT, or OPEN-REC, as appropriate.

2.2.3.2 Initial Calculations

The capacity adjustment factors are calculated in subroutine CAPADJ prior to the actual simulation of the chillers. The capacities must be known ahead of time so that the load allocating routines will be able to calculate how many chillers of each size and type will be needed to meet the cooling load.

The chilled water temperature is calculated in the main PLANT simulation:

$$CHWT = TCOOL + \left[THROTL * \left(\frac{PDEM_2}{CLSUM} \right) - 0.5 \right],$$

where TCOOL is the chilled water temperature at mid-throttling range that corresponds to the keyword CHILL-WTR-T. THROTL is the throttling range of the chiller temperature controller that corresponds to keyword CHILL-WTR-THROTTLE. $PDEM_2$ is the hourly cooling load and CLSUM is the peak cooling load incurred in SYSTEMS. The quantity $PDEM_2$ / CLSUM - 0.5 is not allowed to be larger than 0.5.

In the direct cooling modes, the chilled water temperature is reset to the maximum chilled water temperature for which direct cooling is allowed (keyword DC-CHILL-WTR-T) when the following conditions are satisfied:

1. The outside dry-bulb temperature is less than the maximum outdoor dry-bulb temperature for which direct cooling is allowed (keyword DC-MAX-T), and

2. One of the two direct cooling modes has been selected (keyword DIRECT-COOL-MODE) and is scheduled to be on (keyword DIRECT-COOL-SCH).

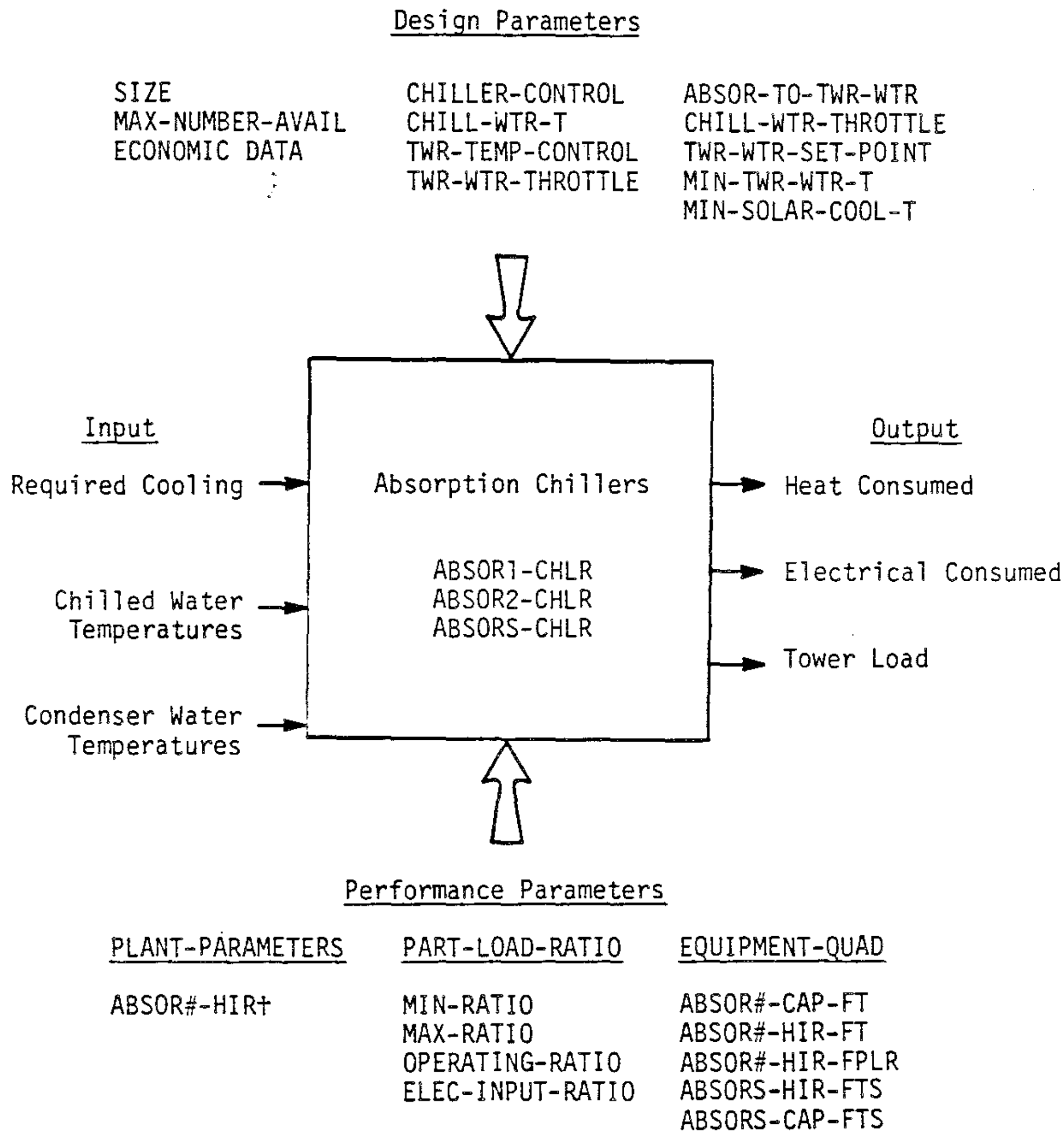
The entering condenser temperature, (ECT) for water cooled condensers is the same as the leaving tower water temperature (TTOWR), which is calculated in subroutine TOWER. If a compression chiller has an air cooled condenser, ECT is the outside dry-bulb temperature, TAIR.

It is suggested that the user read Sec. V.2.2.1, "Use of Adjustment Curves in the Equipment Algorithms," if he has not done so already. This section will give some insight into the way the curves are used to calculate the performance of equipment.

2.2.3.3 Absorption Chillers (subroutine ABSREF)

This algorithm simulates both one- and two-stage absorption chillers with constant temperature heat sources. It also has the capability of modeling a solar fired one-stage absorption chiller (keyword ABSORS-CHLR) with a heat source of varying temperature, although the program does not have any default curves for this type of machine.

The simulation input/output can be illustrated as in Fig. V.8.



† The algorithms for the one-stage, two-stage, and solar absorption chillers are identical. The expression ABSOR# may be replaced with ABSOR1, ABSOR2, or ABSORS.

Fig. V.8. Absorption chiller model.

Algorithm Description

Capacity adjustment factor RCAP - The capacity adjustment calculation is done in CAPADJ prior to the chiller simulation in ABSREF. For one- and two-stage (non-solar fired) machines, the adjustment factor is:

$$RCAP_i = f_7(CHWT,ECT),$$

where f_7 is a bi-quadratic equation whose terms are stored in the array ACAPT and are input through the keyword ABSOR1-CAP-FT (single stage) or ABSOR2-CAP-FT (two-stage). The equation is normalized to the rated (design) point. For example, for a design chilled water temperature of 44°F and entering condenser temperature of 85°F:

$$f_7(44,85) = 1.0.$$

In the direct cooling mode, $RCAP_i$ is set to 0.0.

If the solar-fired absorption chiller is being simulated, an additional factor is needed to take into account the varying temperature of the heat source,

$$RCAP_i = f_7(CHWT,ECT) * f_8(TSOLAR),$$

where TSOLAR is the hot water supply temperature. It is always at least the minimum solar storage tank temperature (MIN-SOL-COOL-T). If the solar tank temperature TNKT is less than the minimum solar storage tank temperature, the boiler is assumed to be supplying the heat at minimum solar storage tank temperature. $f_8()$ is a quadratic equation whose terms are stored in ACAPTS and are input through the keyword ABSORS-CAP-FTS. Note that the solar absorption machine performance curves do not have any default values.

The available capacity is

$$CAP = OPCAP_i * RCAP_i,$$

where $OPCAP_i$ is the sum of the design (rated) capacities of chillers of this type that are operating this hour.

Part load ratio, fraction of hour machine runs - The part load ratio is

$$PL = \frac{LOAD}{CAP},$$

where LOAD is the load on this type of machine. If PLR is less than the minimum part load ratio (RMIN), the machine will be cycling during the hour. The fraction of the hour the machine is on is

$$FRAC = \frac{PL}{RMIN} .$$

RMIN can be input through the MIN-RATIO keyword. FRAC is used in calculating the chiller fluid pump energy.

<u>Heat energy consumption</u> - The heat input ratio temperature correction factor is

$$HIR1 = f_1(CHWT, TTOWR).$$

$f_1()$ is a biquadratic equation whose terms are stored in HIRT and can be input through the keyword ABSOR#-HIR-FT. CHWT is the chilled water temperature and TTOWR is the tower water exit temperature. The equation is normalized to the rated (design) point. For example, the default for $f_1()$ is normalized to $f_1(44,85) = 1.0$.

The simulation of a solar-fired absorption machine requires an additional factor to correct for the varying solar supply temperature,

$$HIRS = f_3(TSOLAR).$$

$f_3()$ is a quadratic equation whose terms are stored in the array HIRTS and can be input through the keyword ABSORS-HIR-FTS.

The heat input ratio correction factor for part load operation is

$$HIR2 = f_2(PL),$$

where $f_2()$ is a cubic equation whose terms are stored in the array HIRPLR and can be input through the keyword ABSOR#-HIR-FPLR. $f_2()$ is assumed to be valid for $0 \le PL \le$ MAX-RATIO, where MAX-RATIO is the maximum fraction of loading allowed. It is normalized so that $f_2(1.0) = 1.0$.

The heat energy consumed is

$$HEAT = CAP * HIRNOM_i * HIR1 * HIR2 * HIRS.$$

$HIRNOM_i$ is the heat input ratio at rated chiller capacity and can be input through the keywords ABSORS-HIR, ABSOR1-HIR, or ABSOR2-HIR, as appropriate.

Electrical energy consumption - The electrical energy needed to power the solution pump or any auxiliaries is

$$ELEC = OPCAP_i * EIR_i * FRAC,$$

where EIR_i is the electric input ratio that can be input through the keyword ELEC-INPUT-RATIO. Note that this algorithm assumes the electrical energy is independent of the LOAD on the machine, unless the machine is cycling.

The total heat rejection to the cooling tower is

$$TOWER = LOAD + HEAT + ELEC.$$

2.2.3.4 Compression Chillers (subroutine COMREF)

This algorithm simulates four types of vapor compression cycle chillers: open centrifugal, hermetic centrifugal, open reciprocating, and hermetic reciprocating. The algorithms for open and hermetic, centrifugal, and reciprocating compression chillers are identical except for the keyword defaults. The algorithm follows the approach developed in Sec. V.2.2.1, "Use of Adjustment Curves in the Equipment Algorithms".

The simulation input/output can be illustrated as in Fig. V.9.

Algorithm Description

Capacity adjustment factor, $RCAP_i$ - The capacity adjustment factor, RCAP, is calculated in routine CAPADJ prior to the simulation in COMREF. RCAP is calculated as

$$RCAP_i = f_7(CHWT, ECT).$$

$f_7()$ is a bi-quadratic equation whose terms are stored in CCAPT and is input through the keyword [-]-CAP-FT.* For direct cooling in the THERMO-CYCLE mode, $f_7()$ is stored in CCAPT5 and is input through the keyword TC-CHLR-CAP-FT. CHWT is the leaving chilled water temperature and ECT is the entering condenser temperature. ECT is either TTOWR if a water cooled condenser or TAIR if air cooled. $f_7()$ should be normalized to the nominal design point. For example, for the default case when CHWT = 44 and ECT = 85:

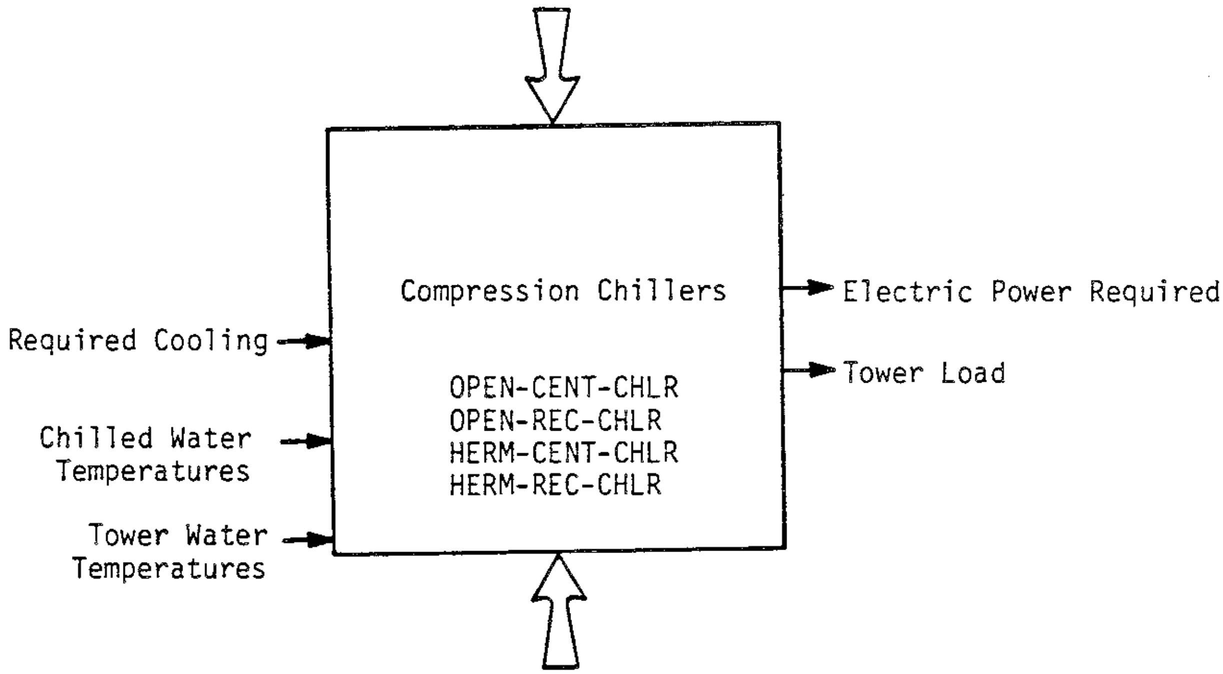
$$f_7(44,85) = 1.0.$$

---

*The symbol [-] may be replaced by OPEN-CENT, OPEN-REC, HERM-CENT, HERM-REC.

Design Parameters

SIZE	CHILLER-CONTROL	
MAX-NUMBER-AVAIL	CHILL-WTR-T	CHILL-WTR-THROTTLE
Economic Data	TWR-TEMP-CONTROL	TWR-WTR-SET-POINT
	TWR-WTR-THROTTLE	COMP-TO-TWR-WTR
	MIN-TWR-WTR-T	MIN-COND-AIR-T
	[-]-COND-TYPE†	



Performance Parameters

PLANT-PARAMETERS	PART-LOAD-RATIO	EQUIPMENT-QUAD
[-]-UNL-RAT	MIN-RATIO	[-]-CAP-FT
OPEN-CENT-MOTOR-EFF	MAX-RATIO	[-]-EIR-FT
OPEN-REC-MOTOR-EFF	OPERATING-RATIO	[-]-EIR-FPLR
	ELEC-INPUT-RATIO	[-]-COND-PWR

†The algorithms for open and hermetic, centrifugal, and reciprocal compression chillers are identical. The symbol [-] may be replaced by OPEN-CENT, OPEN-REC, HERM-CENT, or HERM-REC.

Fig. V.9. Compression chiller model.

In the direct cooling mode, $RCAP_i$ is set equal to 0.0 for the following types of chillers:

1. Reciprocating chillers,
2. Chillers with air cooled condensers.

The available capacity is

$$CAP = OPCAP_i * RCAP_i,$$

where $OPCAP_i$ is the sum of the design (rated) capacities of this chiller type operating this hour.

Part load ratio, cycling, false loading - When the load on a compression chiller drops below a certain point, the chiller may need to use some sort of "false loading" mechanism for further capacity reduction. False loading may be necessary to ensure a high enough refrigerant flow rate through the compressor to prevent surging (in the case of centrifugal machines) or to prevent the evaporator from freezing up. A very common method of false loading a chiller is to bypass hot condenser gas to the evaporator. This mechanism is naturally called "hot gas bypass." As the capacity needed is reduced still further, the compressor may need to start cycling.

The average part load ratio over the hour is

$$PL = \frac{ALOAD}{CAP},$$

where ALOAD is the demand on the machine exclusive of any false loading.

If PL is less than the minimum part load ratio, $RMIN_i$, the machine is cycling on and off. The fraction of the hour the machine is running (FRAC) is

$$FRAC = \frac{PL}{RMIN}.$$

If PL is less than the minimum unloading ratio, $RUNLD_i$, the machine must be false loading. Consequently, as far as the compressor is concerned, the part load ratio must be at least RUNLD.

$$PLR = PL \text{ or } RUNLD_i, \text{ whichever is larger.}$$

$RUNLD_i$ can be input through the keyword [-]-UNL-RATIO.

The compressor load when the compressor is running, including any false loading, is

$$LOAD = CAP * PLR.$$

The false load, taking cycling into account, is

$$FALSLD = (LOAD * FRAC) - ALOAD.$$

Electrical energy consumed - The power correction factor for part load performance is

$$EIR2 = f_5(PLR).$$

$f_5()$ is a quadratic equation whose terms are stored in the array EIRPLR and can be input through the keyword [-]-EIR-FPLR. $f_5()$ is assumed to be valid in the range RUNLD $\leq$ PLR $\leq$ MAX-RATIO. $f_2()$ is normalized so that when PLR = 1.0, $f_5(PLR) = 1.0$.

The power correction factor (EIR1) for off-design temperatures is

$$EIR1 = f_4(CHWT,ECT),$$

where $f_4()$ is a bi-quadratic equation whose terms are stored in the array EIRT and can be input through the keyword [-]-EIR-FT. The default for $f_4()$ is normalized so that at the default design conditions

$$f_4(44,85) = 1.0.$$

Finally, the power consumed is

$$ELEC = CAP * EIR_i * EIR1 * EIR2 * FRAC,$$

where EIR_i is the electric input ratio for design (rated) load given by the keyword ELEC-INPUT-RATIO.

In the direct cooling mode, the compressor does not operate. The power is

$$ELEC = \frac{(AUXIKW) * (3413\ Btu/kW) * (CAP)}{12000\ Btu/ton},$$

where AUXIKW is the additional electric input in the direct cooling mode and is input using the keyword DIRECT-COOL-KW in the units of kW/ton.

If this chiller has an air-cooled condenser, the condenser fan electrical energy is

$$FANE = OPCAP_i * FANELC_i * FRAC,$$

where $FANELC_i$ is the condenser fan electric ratio and corresponds to the keyword [-]-COND-PWR. Note that the algorithm assumes the condenser fan cycles with the compressor.

Heat rejection to tower - If this chiller has a water-cooled condenser, the heat rejected to the cooling tower is

$$TOWER = ALOAD + (ELEC * EFFMOT_i),$$

where $EFFMOT_i$ represents the percent of electrical energy that becomes shaft work on the open chillers. On the closed chillers, all the compressor electrical energy is assumed to be rejected to the tower. EFFMOT may be input through the keyword OPEN-CENT-MOTOR-EFF or OPEN-REC-MOTOR-EFF.

2.2.3.5 Double Bundle Chillers (subroutine DBUNDL)

This algorithm simulates a double bundle compression chiller. This type of chiller is a heat recovery machine; the condenser heat is rejected at a temperature high enough to be used for space heating or low temperature process heat. To accomplish this, two condenser exchange loops are used (hence the term "double bundle").

One exchange loop is in the heat recovery loop, and the second exchange is in the tower loop. The water flow rate in the tower loop can be modulated to maintain a high temperature in the heat recovery loop. Only the excess heat not needed in the heat recovery loop is rejected through the tower loop. Consequently, the performance of a double bundle chiller is independent of the tower temperature during the times heat is being recovered. Instead, the performance is dependent on the water temperature leaving the condenser in the heat recovery loop.

During the times no recoverable heat is needed, the water flow rate through the tower exchange is increased and the dependence of the double bundle chiller performance on the tower temperature is similar to the performance of non-heat recovery type chillers. In the discussion that follows, leaving condenser temperatures are used when in the heat recovery mode, and entering condenser temperatures are used when in the non-heat recovery mode.

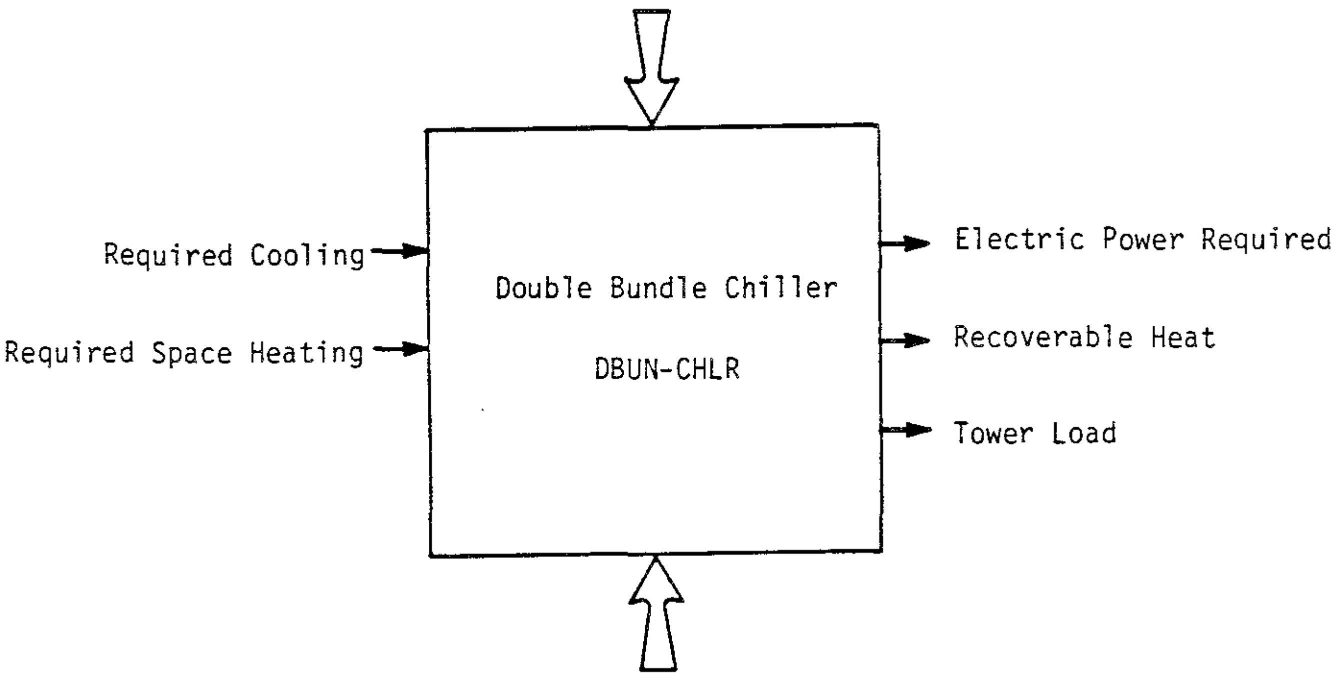
The simulation input/output can be illustrated as in Fig. V.10.

Design Parameters

SIZE
MAX-NUMBER-AVAIL
Economic Data

CHILLER-CONTROL
CHILL-WTR-T
CHILL-WTR-THROTTLE
DBUN-COND-T-REC
DBUN-TO-TWR-WTR

TWR-TEMP-CONTROL
TWR-WTR-SET-POINT
TWR-WTR-THROTTLE
MIN-TWR-WTR-T



Performance Parameters

PLANT-PARAMETERS

DBUN-COND-T-ENT
DBUN-COND-T-REC
DBUN-CAP-COR-REC
DBUN-EIR-COR-REC
DBUN-UNL-RAT-DES
DBUN-UNL-RAT-REC
DBUN-HT-REC-RAT

PART-LOAD-RATIO

MIN-RATIO
MAX-RATIO
OPERATING-RATIO
ELEC-INPUT-RATIO

EQUIPMENT-QUAD

DBUN-CAP-FT
DBUN-CAP-FTRISE
DBUN-EIR-FT
DBUN-EIR-FTRISE
DBUN-EIR-FPLR

Fig. V.10. Double bundle chiller simulation.

Algorithm Description

Capacity adjustment factor, $RCAP_i$ - The capacity adjustment factor, $RCAP_i$, is calculated in routine CAPADJ prior to the simulation in DBUNDL. When the chiller is not in the heat recovery mode, RCAP is calculated as

$$RCAP_i = f_1\ (CHWT, ECT = TTOWR).$$

f_1 is a bi-quadratic equation whose terms are stored in DBCAPT and can be input through the keyword DBUN-CAP-FT. CHWT is the leaving chilled water temperature and ECT is the entering condenser water temperature which, in the non-heat recovery mode of operation, is the tower temperature. The function $f_1()$ is normalized to the design point. For example, for default conditions:

$$f_1(44, TDES) = 1.0,$$

where TDES is the design entering condenser water temperature and may be input through the keyword DBUN-COND-T-ENT.

When in the heat recovery mode, the entering condenser water temperature is no longer important, but the temperature needed for heat recovery is. TDES is substituted for ECT in $f_1()$ and a second factor is added to account for the increased condenser temperature,

$$RCAP_i = f_1(CHWT, ECT = TDES) * RCREC,$$

where RCREC, the heat recovery capacity adjustment factor, can be set by the user through the keyword DBUN-CAP-COR-REC. When defaulted, RCREC will be precalculated in subroutine DEFALT:

$$RCREC = f_2(TRISE),$$

where TRISE is the difference between the leaving condenser water temperature in the heat recovery mode and the leaving condenser water temperature at the design point. TRISE can be calculated easily once the entering temperature at the design point is known. The design exit temperature is calculated from the leaving condenser water temperature in the heat recovery mode, the entering condenser temperature at the design point, the electric input ratio, and the design condenser water flow rate,

$$T_{exit\text{-}des} = \frac{(1 + EIR) * (12000\ Btu/ton)}{(DBWTR) * (8.341\ lb/gal) * (60\ min/hr)} + TDES,$$

where DBWTR, the flow rate to the tower, corresponds to the keyword DBUN-TO-TWR-WTR.

$$TRISE = TREC - T_{exit\text{-}des},$$

where TREC is the leaving condenser temperature in the heat recovery mode, input by DBUN-COND-T-REC.

The available capacity is

$$CAP = OPCAP_i * RCAP_i,$$

where $OPCAP_i$ is the sum of the design (rated) capacities of the double bundle chiller operating this hour.

<u>Part load ratio, cycling, false loading</u> - As described under the compression chiller writeup, a compression chiller may need to use a mechanism such as hot gas bypass to false load the compressor during the hours when the load is small. If the load is very small, the compressor may need to cycle on and off, as well as be false loaded. Because the double bundle chiller is a compression machine, its operation is similarly affected. Moreover, it may need to be false loaded at a higher part load ratio when in the heat recovery mode because of the higher condenser temperature (and pressure).

The average part load ratio over the hour is

$$PL = \frac{ALOAD}{CAP},$$

where ALOAD is the demand on the machine exclusive of any false loading. If PL is less than the minimum part load ratio, $RMIN_i$, the machine is cycling on and off. The fraction of the hour that the machine is running is

$$FRAC = \frac{PL}{RMIN}.$$

RMIN can be input by the keyword MIN-RATIO.

If PL is less than the minimum unloading ratio, $UNLOAD_i$, the machine must be false loading. Hot gas bypass is occurring and the compressor is operating at a part load ratio greater than PL. $UNLOAD_i$ can have a different value depending on whether the chiller is in the heat recovery mode or not. $UNLOAD_i$ corresponds to the keywords DBUN-UNL-RAT-DES and DBUN-UNL-RAT-REC. The part load ratio the compressor is operating at is

$$PLR = PL \text{ or } UNLOAD_i,$$

whichever is greater.

The compressor load including any false loading and excluding any cycling is

$$LOAD = CAP * PLR$$

and the false load, taking cycling into account, is

$$FALSLD = (LOAD * FRAC) - ALOAD.$$

<u>Electrical energy consumed</u> - The power correction factor for part load performance is

$$EIR2 = f_2(PLR),$$

where $f_2()$ is a quadratic equation whose terms are stored in the array EIRPLR and can be input through the keyword DBUN-EIR-FPLR. $f_2()$ is normalized so that when PLR = 1.0, $f_2(PLR) = 1.0$.

The power correction factor for off-design temperatures in the non-recovery mode is

$$EIR1 = f_1(CHWT, ECT = TTOWR),$$

where $f_1()$ is a bi-quadratic equation whose terms are stored in EIRT and can be input through the keyword DBUN-EIR-FT. The default for $f_1()$ is normalized so that the default design conditions are

$$f_1(44, TDES = 85) = 1.0.$$

The power consumed in the non-recovery mode is

$$ELEC = CAP * EIR_i * EIR1 * EIR2 * FRAC,$$

where EIR_i is the nominal electric input ratio input by the keyword ELEC-INPUT-RATIO.

When in the heat recovery mode, the entering condenser water temperature is not important and an additional term is added to correct for the rise in condenser temperature

$$EIR1 = f_1(CHWT, ECT = TDES)$$

$$ELEC = CAP * EIR_i * EIR1 * EIR2 * RKWREC,$$

where RKWREC, the heat recovery power adjustment factor, can be input by the user through the keyword DBUN-EIR-COR-REC. When defaulted, RKWREC will be precalculated in subroutine DEFALT:

$$RKWREC = f_6(TRISE),$$

where f_6 is a quadratic equation whose terms are stored in EIRREC and can be input through the keyword DBUN-EIR-FTRISE.

In the direct cooling mode, the compressor does not operate. The power consumed is

$$ELEC = \frac{(AUXIKW) * (3413\ Btu/kW) * (CAP)}{(12000\ Btu/ton) * (FRAC)},$$

where AUXIKW is the additional electric input used in the direct cooling mode. AUXIKW is input through keyword DIRECT-COOL-KW in the units of kW/ton.

Heat rejection - The heat rejected to the cooling tower in the non-recovery mode is

$$TOWER = ALOAD + ELEC.$$

When recovering heat, only some fraction of the total heat rejection capacity can be recovered. This fraction depends on the size of the heat recovery bundle. The amount of heat recoverable is

$$HTREC = TOWER$$

or

$$HTREC = (1. + EIR_i) * OPCAP * RRECVR,$$

whichever is smaller. The second expression is the maximum quantity of the heat rejected at full load in the non-heat-recovery mode that can be recovered. RRECVR is the fraction of recoverable rejected heat and corresponds to the keyword DBUN-HT-REC-RAT. The heat rejected to the tower is reduced by HTREC. HTREC is stored in the heat recovery supply array $HTAVAL_i$.

The heat recovery routine is called after DBUNDL. It attempts to utilize HTREC to meet any heating loads the double bundle chiller is hooked up to. Any portion of HTREC that is not usable in the heat recovery routine is rejected to the cooling tower. No heat recovery is available in the direct cooling mode.

2.2.3.6 Cooling Tower (subroutines TOWERD and TOWER)

Subroutine TOWERD designs appropriate cooling towers and calculates values for certain variables. Subroutine TOWER simulates user-specified or default-designed towers on an hourly basis.

The algorithm used for ceramic cooling towers (keyword CERAMIC-TWR) is the same as the one for conventional cooling towers (keyword COOLING-TWR) with the exception of the default economic data. The ceramic tower has a higher first cost and lower maintenance costs.

The four basic types of cooling towers modeled are:

1. induced-draft crossflow,
2. induced-draft counterflow,
3. forced-draft crossflow, and
4. forced-draft counterflow.

The four classifications are related to the fan location and to the direction of the air flow relative to the water flow. Induced-draft towers have the fans located at the air exit, whereas forced-draft towers have the fans at the air entrance. This model is capable of simulating all four types because of the "Tower Unit" (TU) or "relative area" (A_r) concept.

The "90-80-70 point" is a reference standard that refers to water entering the tower at 90°F and leaving the tower at 80°F, when the wet-bulb temperature is 70°F. One gpm of water cooled under these conditions is defined as one tower unit (TU).

Variable List:

Keyword	FORTRAN Variables	Engineering Variables	Description
	APP	A_p, APP	The approach is how close the water temperature gets to the wet-bulb temperature. $A_p = T_{out} - T_{wetbulb}$. A cooling tower of 1 TU size, at the 90-80-70 point, has an approach of A_p = 80°F - 70°F, or 10°F.
	AREA	A_r, AREA	The relative area is the capacity of a cooling tower in Tower Units (see TU).
SIZE	ARCELL	ARCELL	The area of one cell of a cooling tower in Tower Units.
	CAPCLR	CAPCLR	The total chiller capacity.

Keyword	FORTRAN Variables	Engineering Variables	Description
	CFMCOR	CFMCOR	The rating factor air flow correction.
RFACT-CFM-EXPONENT	CFMEXP	CFMEXP	The exponent used to modify the rating factor for off-design air flows.
TWR-FAN-LOW-CFM	CFMLOW	CFMLOW	Specifies air flow rate through the tower when fan is on low speed, divided by the flow rate at high speed (ratio).
TWR-FAN-OFF-CFM	CFMOFF	CFMOFF	The air flow rate when fans are off divided by high speed flow rate.
COMP-TO-TWR-WTR ABSOR-TO-TWR-WTR or DBUN-TO-TWR-WTR	CGPM	CGPM	The ratio of cooling tower water flow (gpm) to chiller capacity (tons).
	CLSUM	CLSUM	The peak cooling load incurred in the SYSTEMS simulation.
	DESGPM	DESGPM	The maximum water flow rate from all chillers (total).
	DESLD	DESLD	The maximum heat rejection load that might be experienced.
	EFAN	EFAN	The fan electrical energy consumption in Btu/hr. (whole tower).
	EFCELL	EFCELL	The energy consumption of fans in one cell.
TWR-IMPELLER-EFF	EFFIMP	EFFIMP	The efficiency of the tower circulation pump impeller.
TWR-MOTOR-EFF	EFMOT	EFMOT	The efficiency of the tower pump motor.
ELEC-INPUT-RATIO	EIR	EIR	The electric input ratio for equipment.
TWR-FAN-LOW-ELEC	ELCLOW	ELCLOW	The ratio of power consumed by fans at low speed to the power consumed at high speed.
	EPUMP	EPUMP	The electrical energy consumed by the condenser water pump.

Keyword	FORTRAN Variables	Engineering Variables	Description
	ESPEED	ESPEED	The fan speed electrical input ratio.
	EXTRA	EXTRA	The heat rejected that does not come directly from the chillers, Btu/hr.
	FRAC	FRAC	The fraction of the hour the tower fans are operated at higher speed to accommodate a tower overload.
TWR-CELL-MAX-GPM	GALMAX	GALMAX	The ratio of maximum water flow per tower cell to the design water flow.
	GPM	GPM, gpm	The water flow rate to the cooling tower, gpm.
	GPMMAX	GPMMAX	The maximum water flow rate per cell.
TWR-PUMP-HEAD	HEAD	HEAD	The pressure head in tower water circulation loop.
	HIR	HIR	The heat input ratio of absorption chillers.
	ISPEED	ISPEED	The tower fan speed index.
	LOAD	LOAD	The heat rejection load of the tower. Btu/hr
	MINCELL	MINCELL	The minimum number of tower cells allowed for the given gpm.
MAX-NUMBER-AVAIL	NCELL	NCELL	The number of cells in the tower.
	OPCAP	OPCAP	The capacity of chillers operating this hour.
	PDEM	PDEM	The cooling load determined in SYSTEMS simulation.
	RANGE	R, RANGE	The range is the temperature drop (°F) of the water as it flows through the tower. A cooling tower of 1 TU size, at the 90-80-70 point, has a range of R = 90°F - 80°F, or 10°F.
	RNGNOM, CDESDT	RNGNOM, CDESDT	The design range of the cooling tower (temperature drop).

Keyword	FORTRAN Variables	Engineering Variables	Description
TWR-RFACT-FRT	R1	R_1, R1	The rating factor term as a function of range and wet-bulb temperature.
TWR-RFACT-FAT	R2	R_2, R2	The rating factor term as a function of approach and wet-bulb temperature.
	RF, RFACT	RF, RFACT, F_r	The rating factor, which is the relative area (TU) divided by the water flow rate (gpm) at the design air flow rate. $$F_r = \frac{A_r}{gpm}$$ if the gpm is the design gpm, then $F_r = 1$. If the air flow rate through the tower is altered by varying the fan speed or by using other control techniques, then the previous expression must be modified as follows: $$F_r = \left[\frac{\dot{M}_{air}}{\dot{M}_{air-design}}\right]^p * \frac{A_r}{gpm} \qquad (V.3)$$ where $\dot{M}_{air}$ is the actual air flow rate, $\dot{M}_{air-design}$ is the design air flow rate, and p has values in the range of 0.6 to 1.1. P = 0.9 is the default value. Equation (V.3) is a semi-empirical expression that is most accurate when $\dot{M}_{air}$ does not differ significantly from the design value.
TWR-WTR-THROTTLE	THROTL	THROTL	The effective throttling range about the cooling tower temperature set point.
MIN-TWR-WTR-T	TMIN	TMIN	The minimum for exiting cooling tower water, °F.
	TOTCAP	TOTCAP	The total capacity of all chillers, Btu/hr.

Keyword	FORTRAN Variables	Engineering Variables	Description
	TPUMPR	TPUMPR	The condenser pump electric input ratio, Btu/gpm.
TWR-WTR-SET-POINT	TSET	TSET	The cooling tower exiting water temperature set point, °F.
	TTOWR	TTOWR	The exiting tower water temperature, °F.
		TU	A tower unit is a method of sizing cooling towers. One TU is the cooling surface plan area required to process one gpm of water at the 90-80-70 point. Restated, a tower having 100 TU can cool 100 gpm of 90°F water by 10°F when the wet-bulb temperature is 70°F. The actual cooling surface per Tower Unit may vary with the design of the tower. The Tower Unit allows towers of different designs and surface areas to be compared (and, for our purposes, simulated by the same model).
TWR-DESIGN-WETBULB	TWBDES	TWBDES	The wet-bulb temperature used to design a cooling tower (subroutine TOWERD).
	TWET	TWET, T_{wb}	The wet-bulb temperature, °F.
		90-80-70 point	A reference standard referring to water entering the tower at 90°F, leaving at 80°F, when the wet-bulb temperature is 70°F.

2.2.3.6.1 Determination of the Parameters Relative Area (A_r), Rating Factor (F_r), and Approach (A_p)

Relative Area (A_r) - The relative area (A_r) depends only on the cooling tower design (fill material, number of cells, etc.) and is not a function of the operating parameters such as R, A_p, or gpm. For a multi-cell tower having N_o cells with each cell having its own air circulation fan, the relative area associated with each cell can be denoted by A_{rn}. If water is circulated through N cells, ($N < N_o$), then the relative area in use is $A_r = N * A_{rn}$; whereas for operation of all the cells

$$A_{ro} = N_o * A_{rn}.$$

Because A_r is based on the tower unit (TU) definition, A_r is not equal to the physical plan area of a tower. Two different tower designs can have the same relative areas, yet their physical plan areas can be different. The advantage of the relative area or tower unit concept is that F_r becomes unity at the 90-80-70 point for all towers, and the performance rating charts (relating F_r, R, A_p, T_{wb}) become similar for the various types of tower designs; thereby permitting simulation of all mechanical-draft units with a single analytical model (Ref. 3).

Because A_r is constant for a given tower, the rating factor, F_r, also is a constant as long as the water and air flows remain fixed [Eq. (V.3)]. Performance charts for the wet-bulb temperature, T_{wb} = 60, 70, and 80°F are reproduced as Figs. V.11 through V.13. These are the charts used to produce the performance curves used in DOE-2.1. Using these performance charts, it is possible in principle to express any one of the parameters F_r, R, A_p, and T_{wb} in terms of the other three, e.g., $F_r = f(A_p, R, T_{wb})$, $R = f(F_r, A_p, T_{wb})$, etc. The rating factor (F_r), relative area (A_r), and flow rates (gpm and $\dot{M}_{air}$) are in turn related through Eq. (V.3), that is,

$$F_r = \left[\frac{\dot{M}_{air}}{\dot{M}_{air-design}}\right]^p * \frac{A_r}{gpm} .$$

Equation (V.3) may be rewritten as

$$A_r = F_r * gpm * \left[\frac{\dot{M}_{air-design}}{\dot{M}_{air}}\right]^p . \qquad (V.3a)$$

If the air flow rate is the design air flow rate, this equation becomes

$$A_r = F_r * gpm. \qquad (V.3b)$$

On the performance charts (Figs. V.11 through V.13), it can be seen that when the range increases, with A_p and T_{wb} held constant, F_r also increases. Hence, for a given water flow rate, more tower units are needed to cool the water [Eq. (V.3b)]. If, for a given range and wet-bulb, the water is allowed to leave the tower at a higher temperature (therefore, a higher approach), fewer TU are needed. Finally, for a given range and approach, fewer TU are needed if the wet-bulb temperature is increased.

All of the above information is used in the simulation in one of two ways:

(a) Assuming the desired water exit temperature can be met, how many tower cells, at what fan speeds, are required?

(b) If the desired water exit temperature cannot be met (with all fans of all cells operating on high speed), what is the exiting water temperature?

All other parameters are known. The range and water flow rates are determined by the chillers, the wet-bulb is a function of the weather, and the rated area per cell, in TU, has been calculated from the users input by the tower design routine.

<u>Solution (a) - Find the Number of Operating Cells and the Fan Speeds Required to Hold the Set Point Temperature</u>

The leaving water temperature is assumed to be known, and the number of operating cells and the fan speeds are to be calculated.

The approach is

$$A_p = TTOWR - T_{wb}.$$

The rating factor at the design air flow rate can be determined from the performance charts, or by a curve fit to the charts

$$F_r = f(A_p, R, T_{wb}).$$

If the air flow rate is less than the design air flow rate, the rating factor would be modified,

$$F_r = f(A_p, R, T_{wb}) * \left[\frac{\dot{M}_{air-design}}{\dot{M}_{air}}\right]^p. \qquad (V.3c)$$

The area in TU for these conditions is then

$$AREA = gpm * F_r. \qquad (V.3d)$$

The number of tower cells needed for this AREA is the area calculated in Eq. (V.3d) divided by the area/cell

$$NCELL = \frac{AREA}{ARCELL}, \text{ rounded up}. \qquad (V.3e)$$

If NCELL is greater than MAX-NUMBER-AVAIL, the tower does not have enough cells to cool the water to the assumed exiting temperature. The simulation initially assumes in Eq. (V.3c) that the air flow rate is that due to free convection with the fans off. The ratio of the actual air flow to the design air flow when the fans are off is specified by the keyword TWR-FAN-OFF-CFM. If the air flow rate with the fans off does not give enough capacity, the fans are set to the low speed (TWR-FAN-LOW-CFM), which assumes the tower has two-speed motors. Otherwise, the fans are set directly to high, which assumes the motors are one-speed. The simulation repeats the calculations in Eqs. (V.3c) through (V.3e). If the fans are on high speed and the tower does not have enough cells to cool the water, the assumed exiting temperature is too low, and the simulation must go to Solution (b) to find the water temperature (at this point, the program knows that the fans in all cells are on high speed).

If, on the other hand, the tower does have enough capacity to hold the water temperature at the set point, the simulation must prevent the water temperature from falling below this set point. The simulation assumes that fan cycling is used for this purpose. A one-speed fan can cycle between off and high; a two-speed fan can cycle between off and low or low and high.

The area needed at the higher speed is less than the area being used. Similarly, the area needed at the lower speed is greater than the area being used. The fraction of the hour that the tower is at the higher speed is calculated as

$$FRAC = \frac{ARLOW - (ARCELL * NCELL)}{ARLOW - AREA} ,$$

where ARLOW is the tower area needed at the lower speed, (ARCELL * NCELL) is the area in use, and AREA is the area needed at the higher speed.

Solution (b) - Find the Water Exit Temperature That is Floating Above the Set Point Temperature

The user has the option to input the TWR-TEMP-CONTROL as either FLOAT or FIXED. If the default, FLOAT, is chosen, the water exit temperature is assumed to be 10°F above the wet-bulb (approach of 10°F) for regular cooling (for direct cooling, this temperature difference is assumed to be (.5 * THROTL). If FIXED is chosen, the water exit temperature is at the TWR-WTR-SET-POINT, corrected by the TWR-WTR-THROTTLE. Solution (a) is first attempted to see if this exit temperature is possible. If it isn't, i.e., more rated area is needed to produce this temperature than is in the tower, then the water exiting temperature must be floating out of control, above the set point temperature. In this case, this temperature is determined as follows.

The total area of the tower is

$$AREA = ARCELL * MAX\text{-}NUMBER\text{-}AVAIL.$$

The water flow rate has been set by the chillers, and the fans must be operating at full speed, if the temperature is floating above the set point. The rating factor is, therefore:

$$F_r = \frac{AREA}{gpm}.$$

The range has been set by the chillers (heat rejection / lbs water flow) and the wet-bulb temperature is known. The approach can be found from the performance charts, or by an equation fitted to the charts:

$$A_p = f(F_r, R, T_{wb}).$$

The leaving water temperature is then

$$TTOWR = T_{wb} + A_p.$$

60° Wet Bulb Chart

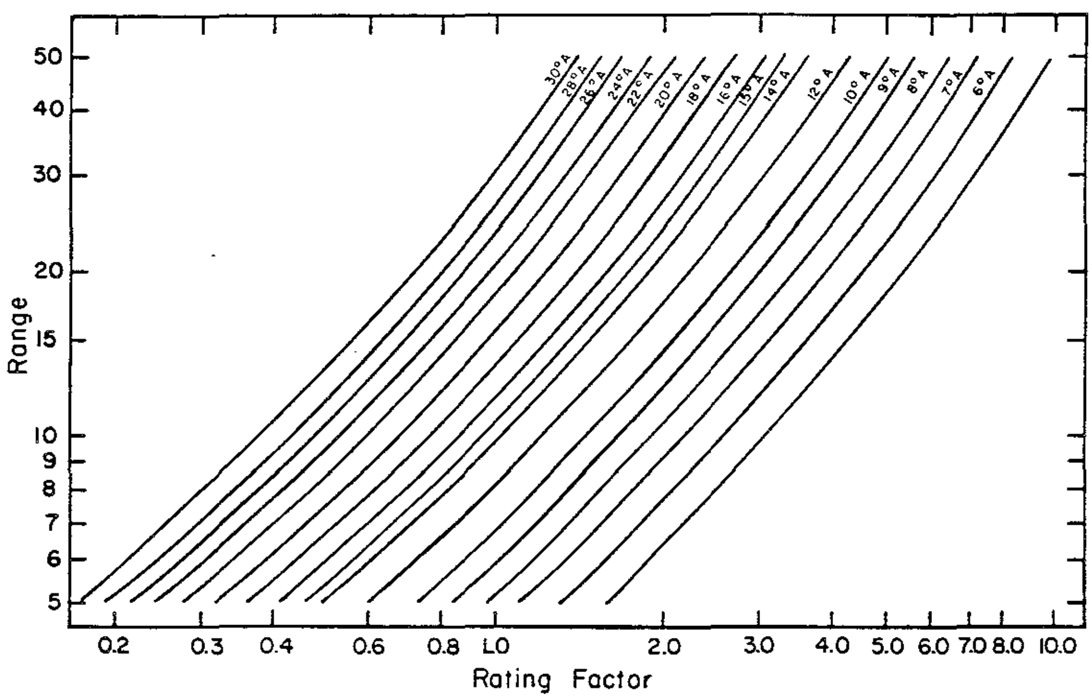


Fig. V.11. Cooling Tower Performance Chart for T_{wb} = 60°F.

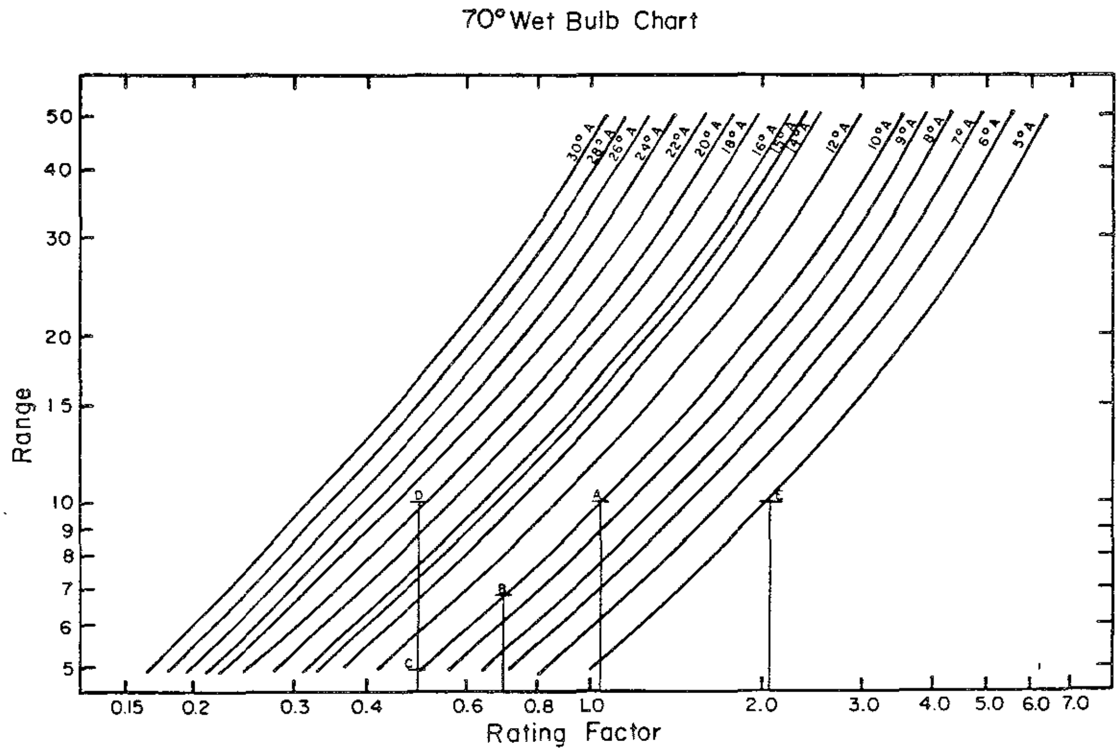


Fig. V.12. Cooling tower performance chart for T_{wb} = 70°F.

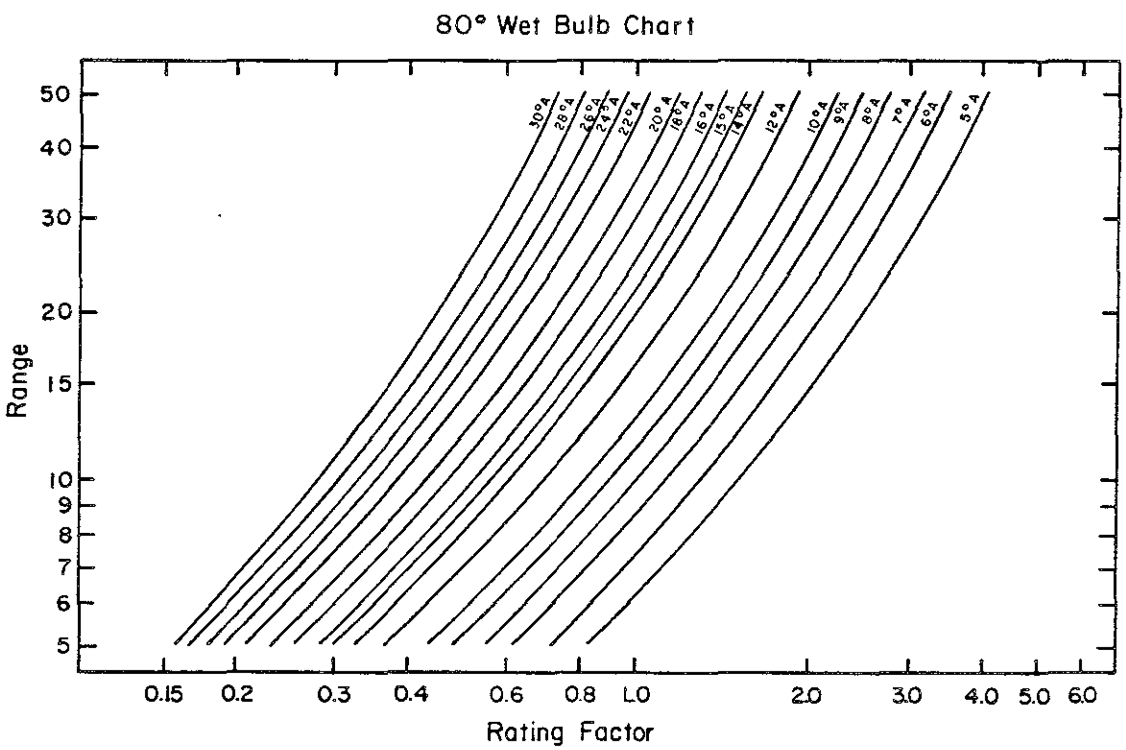


Fig. V.13. Cooling tower performance chart for T_{wb} = 80°F.

Rating factor F_r - The curves used to determine the rating factor (F_r) and the approach (A_p) can be expressed as:

$$F_r = f(R, A_p, T_{wb})$$

and

$$A_p = f(F_r, R, T_{wb}).$$

Each of these curves has three independent variables. DOE-2.1 has the capability of using equations of, at most, two independent variables. For this reason, the equations will be broken down into components in such a way that they can be combined to yield the intended result.

Figures V.11 through V.13 are used to derive the curves. The figures have the following boundary conditions:

$$60 < T_{wb} < 80,$$
$$5 < A_p < 30, \text{ and}$$
$$5 < R < 50.$$

The constraints chosen for the curve fits are:

$$60 < T_{wb} < 80,$$
$$5 < A_p, < 20, \text{ and}$$
$$5 < R < 10.$$

The simulation will have to do some extrapolation to extend these boundaries:

$$30 < T_{wb} < 85,$$
$$2 < A_p, \text{ and}$$
$$0 < R.$$

These boundaries were felt to be reasonable and consistent with the various default parameters for the tower and chillers. The user is cautioned about overriding defaults that may cause A_p or R to become very large (COMP-TO-TWR-WTR, or TWR-WTR-SET-POINT for example).

According to the definition, F_r at the 90-80-70 point has the value 1.0. This corresponds to a wet-bulb temperature of 70°F, approach of 10°F, and a range of 10°F. This point can be located in the family of curves shown in Figs. V.11 through V.13 and will be the reference point (point A in Fig. V.12.

It can be seen from Fig. V.12 that the log of F_r is what is being plotted. Therefore, the curves the program uses will be in terms of $\log_{10} F_r$.

$$\log_{10} F_r = f(R, A_p, T_{wb}).$$

Using these coordinates

$$\log_{10} F_r = f(10, 10, 70) = 0.0.$$

Hence, the reference point in the logarithmic coordinates is 0.

The function $f(R, A_p, T_{wb})$ is broken into two parts

$$f(R, A_p, T_{wb}) = f1(R, T_{wb}) + f2(A_p, T_{wb}) \text{ so that}$$

$$F_r = 10^{(f1 + f2)}.$$

f1 corresponds to curve ABC in Fig. V.12. Varying the range will cause log F_r to move up and down on this curve. Varying the wet-bulb temperature will cause ABC to translate and rotate slightly. f2 corresponds to line DAE in Fig. V.12. Once f1 has determined the point on curve ABC, f2 moves the point horizontally (constant range) to correct for approaches other than 10°F. Comparing Fig. V.12 with Figs. V.11 and V.13, it can be seen that a lower wet-bulb temperature causes the curves to spread out (causing DAE to become longer), hence, the wet-bulb temperature dependence of f2. It can be seen that the family of approach curves tends to converge slightly for lower values of the range (Fig. V.13). It may be that f2 should be corrected for this convergence; however, when the range is between 5°F and 10°F, this convergence is at most 4 percent of the value of DAE. The gain in accuracy was felt to be too small for this convergence factor to be included.

<u>Approach (A_p)</u> - The third factor that must be developed is

$$A_p = A(F_r, R, T_{wb}).$$

This equation was used in the situations discussed earlier when the rating factor, range, and wet-bulb temperature are known, and the approach is needed. In the above curve fit for F_r, the relation

$$\log F_r = f1(R, T_{wb}) + f2(A_p, T_{wb})$$

was developed. This can be rearranged as

$$f2(A_p, T_{wb}) = \log F_r - f1(R, T_{wb}).$$

Let $x = \log F_r - f1(R, T_{wb})$. Then,

$$f2(A_p, T_{wb}) = x.$$

f2 can be inverted to yield A_p

$$A_p = A(x, T_{wb}).$$

X is simply the distance along line DAE from curve ABC. It is the dependent value of $f2(A_p, T_{wb})$. If x is 0, then the approach is 10°F.

2.2.3.6.2 Cooling Tower Design and Calculations (subroutine TOWERD)

These calculations are performed at the beginning of the PLANT simulation. Their purpose is to determine the size of the tower (in TU) if the user has not specified a tower, the electrical consumption of the condenser water pump and the fans, and miscellanous variables needed in the hourly simulation.

The simulation is performed in the following order:

1. Estimate load.
2. Determine number of cells.
3. Determine water flow rate.
4. Determine circulation pump energy.
5. Determine design range (R or RANGE).
6. Determine design approach (A_p or APP).
7. Determine design rating factor (F_r, RF, or RFACT).
8. Determine tower area (A_r or AREA).
9. Determine fan energy.
10. Miscellaneous calculations.

Algorithm Description

Step 1. Estimation of the tower load.

If the user has input a tower size, then steps 1 and 2 are skipped. The estimated tower load is based on the design total heat rejection of the chillers that have water-cooled condensers.

$$\text{LOAD} = \sum_{i}^{\substack{\text{number of all}\\ \text{chillers}}} \text{TOTCAP}_i * (1 + \text{EIR}_i)$$

$$+ \sum_{i=1}^{\substack{\text{number of all}\\ \text{absorption chillers}}} \text{TOTCAP}_i * (1 + \text{HIR}_i),$$

where HIR_i is the heat input ratio of each absorption machine, EIR_i is the electric input ratio of each chiller, and $TOTCAP_i$ is the design (rated) capacity of each chiller.

Step 2. Number of tower cells (NCELL).

The algorithm will try to give the cooling tower four cells if possible. In no case will a cell be larger than 15 million Btu and, if possible, will not be smaller than one million Btu. This step is skipped if the user has input the size of the cell.

Step 3. Design water flow rate.

The design water flow rate to the tower is the sum of the water flow rates of the chillers that have water-cooled condensers.

$$\text{GPM} = \sum_{i}^{\substack{\text{number of all}\\ \text{compression chillers}}} \frac{[(\text{TOTCAP}_{comp,i}) * (\text{CGPM}_{com,i})]}{12000 \text{ Btu/ton}}$$

$$+ \sum_{i}^{\substack{\text{number of all}\\ \text{absorption chillers}}} \frac{[(\text{TOTCAP}_{ABS,i}) * (\text{CGPM}_{ABS,i})]}{12000 \text{ Btu/ton}}$$

$$+ \sum_{i}^{\substack{\text{number of all double}\\ \text{bundle chillers}}} \frac{[(\text{TOTCAP}_{DBUN,i}) * (\text{CGPM}_{DBUN,i})]}{12000 \text{ Btu/ton}}$$

where $TOTCAP_{[\_],i}$ is the design (rated) capacity of the compression, absorption, and double bundle chillers respectively and CGPM is the required

GPM/ton for each chiller (input through keywords COMP-TO-TWR-WTR, ABSOR-TO-TWR-WTR, or DBUN-TO-TWR-WTR as appropriate).

The maximum water flow rate/cell is

$$GPMMAX = \frac{GPM}{NCELL * GALMAX},$$

where GALMAX is the maximum number of gallons allowed per cell (keyword TWR-CELL-MAX-GPM).

Step 4. Condenser water circulation pump energy ratio.

The condenser water circulation pump energy ratio is

$$TPUMPR = \frac{\left(.643 \frac{\text{Btu-min}}{\text{ft-gallons-hr}}\right) * (HEAD)}{(EFMOT) * (EFFIMP)},$$

where HEAD is the pressure head in the tower water circulation loop (keyword TWR-PUMP-HEAD), EFMOT is the tower pump motor efficiency (keyword TWR-MOTOR-EFF) and EFFIMP is the tower circulation pump efficiency (keyword TWR-IMPELLER-EFF).

When multiplied by the hourly GPM, this gives the pump electrical consumption. The pump energy consumption is added to the design heat rejection load

$$LOAD = LOAD + (GPM * TPUMPR * EFMOT).$$

Step 5. Design range (RNGNOM).

The design range (temperature drop) is

$$RNGNOM = \frac{LOAD}{(GPM) * (8.34\ \text{lb/gal}) * (60\ \text{min/hr})}.$$

Step 6. Design approach (APP).

The user has the option to input the tower temperature control (keyword TWR-TEMP-CONTROL) as either FLOAT or FIXED. If the control is FLOAT, the exit water temperature, TTOWR = TWBDES + 10°F for regular cooling. If the control is FIXED, TTOWR = TSET + (.5 * THROTL). In all cases, TTOWR must be above TMIN.

$$APP = TTOWR - TWBDES,$$

where TWBDES is the tower design wet-bulb temperature (keyword TWR-DESIGN-WET-BULB), TSET is the temperature set point (keyword TWR-WTR-SET-POINT), THROTL is the temperature throttling range (keyword TWR-WTR-THROTTLE) and TMIN is the minimum allowable water temperature (keyword MIN-TWR-WTR-T).

A check is made to insure that the approach is at least ten degrees.

Step 7. Design rating factor RFACT (TU/gpm). (See Sec. V.2.2.3.6.1 for an explanation of Rating Factor).

The rating factor term (R1) for the design range and wet-bulb temperature is

$$R1 = f(RNGNOM, TWBDES)$$

where f is a bi-linear or bi-quadratic equation input through keyword TWR-RFACT-FRT.

The rating factor term (R2) for the design approach and wet-bulb temperature is

$$R2 = f(APP, TWBDES)$$

where f is a bi-linear or bi-quadratic equation input through keyword TWR-RFACT-FAT.

The design rating factor is

$$RFACT = 10^{(R1 + R2)}.$$

Step 8. Required area of the tower.

The required area of the tower (in tower units) is

$$AREA = GPM * RFACT.$$

The area per cell is

$$ARCELL = \frac{AREA}{NCELL}.$$

Step 9. Electrical power.

The electrical power at the design cfm per cell is either

1. EFCELL = f(ARCELL) where f is a linear or quadratic expression input by keyword TWR-FAN-ELEC-FTU, or

2. if the user input the tower electric input ratio, EIR, using keyword ELEC-INPUT-RATIO,

EFCELL = (LOAD/NCELL)(EIR).

Step 10. Miscellaneous calculations.

The fan speed electrical consumption ratios are stored for hourly use in ESPEED

off ESPEED(1) = 0,
low ESPEED(2) = ELCLOW,
high ESPEED(3) = 1.0,

where ELCLOW is the ratio of fan power consumed at low speed to fan power consumed at high speed (keyword TWR-FAN-LOW-ELEC).

If the air flow rate is less than the design air flow rate, the rating factor would be modified by the rating factor air flow correction.

The air flow correction is precalculated and stored in CFMCOR. Because of the way it is used in the hourly calculations, the inverse is stored.

For fan off, $CFMCOR(1) = \left(\frac{1.0}{CFMOFF}\right)^{CFMEXP}$,

for fan low, $CFMCOR(2) = \left(\frac{1.0}{CFMLOW}\right)^{CFMEXP}$,

for fan high, CFMCOR(3) = 1.0,

where CFMOFF is the cfm with fan off (keyword TWR-FAN-OFF-CFM), CFMLOW is the cfm on low speed (keyword TWR-FAN-LOW-CFM) and CFMEXP is the correction factor exponent (keyword RFACT-CFM-EXPONENT). See Sec. V.2.2.3.6.1 for more explanation.

There are several variables that are used to guess the tower temperature for those hours when the tower did not operate the hour before. They are the maximum heat rejection load that might be experienced (DESLD), the maximum water flow rate (DESGPM), and the total chiller capacity (CAPCLR). These variables are also stored for the hourly simulation.

2.2.3.6.3 Hourly Tower Simulation (subroutine TOWER)

During the hourly simulation the tower parameters are calculated in the following order:

1. Determine load, water flow rate, and pump power required for flow rate. The pump heat is then added to the tower load.

2. Determine the minimum number of cooling tower cells required for this flow rate.

3. Determine the range (R).

4. Set the tower exit temperature.

5. Determine the approach (A_p) for this exit temperature.

6. Set the fan speed.

7. Calculate rating factor (F_r).

8. Calculate area of tower required for these conditions; the number of cells must be the larger of this number or the number in step 2.

   If the number of tower cells has been specified by the user to be less than the number required, then the fan speed is increased and steps 6-8 are repeated.

9. If there is still not enough tower capacity, a higher tower exit temperature is calculated.

10. Determine total power required.

Note that several steps are very similar to those in subroutine TOWERD (Sec. 2.2.3.6.2). The major difference is that the actual load each hour is simulated here where TOWERD assumes the maximum possible load for tower sizing.

Step 1. Determine Water Flow Rate, Pump Energy, and Tower Load.

The condenser water flow rate to the tower is

$$GPM = \sum_{i=1}^{\text{number of watercooled compression chillers}} [(OPCAP_i) * (CGPM_i)] \text{ for each compression chiller operating this hour}$$

$$+ \sum_{i=1}^{\text{number of double bundle chillers}} [(OPCAP_i) * (CGPM_i)] \text{ for each double bundle chiller operating this hour}$$

$$+ \sum_{i=1}^{\text{number of absorption chillers}} [(OPCAP_i) * (CGPM_i)] \text{ for each absorption chiller operating this hour}$$

$$+ \frac{EXTRA}{(8.341 \text{ lbs/gal}) * (60 \text{ min/hr}) * (10^{\circ}F)} ,$$

where OPCAP is the operating capacity of the chiller this hour, CGPM is the required GPM/ton for each chiller type, and EXTRA is the heat to be rejected by the tower that does not come directly from the chillers. This heat is either last hours recoverable double bundle chiller heat that was not recovered or heat rejected by the California heat pumps in the SYSTEMS simulation (Note: for heat pump loads to be rejected from SYSTEMS, there can be no chillers in PLANT). The EXTRA heat rejected is assumed to be at the flow rate needed for a 10° temperature drop through the tower.

If the cooling tower is being used in the direct cooling STRAINER-CYCLE mode, all of the chillers remain unused. The condenser water flow rate is based on the installed capacity or the calculated capacity of the towers and the design range

$$GPM = \frac{CLSUM}{(CDESDT) * (8.341 \text{ lbs/gal}) * (60 \text{ min/hr})} ,$$

where CLSUM is the peak cooling load incurred in the SYSTEMS simulation, and CDESDT is the design temperature drop through the SYSTEMS cooling loop (keyword CCIRC-DESIGN-T-DROP). This number will correspond to the chilled water flow rate.

The energy used by the condenser water circulation pump is

$$EPUMP = GPM * TPUMPR,$$

where TPUMPR was calculated by subroutine TOWERD.

In the direct cooling STRAINER-CYCLE mode, the circulation pump power is calculated to include the strainer resistance

$$EPUMP = \frac{(AUXIKW) * (3413\ Btu/kW\text{-}hr) * (CLSUM)}{12000\ Btu/ton},$$

where AUXIKW is the additional electric input for the strainer and is input through keyword DIRECT-COOL-KW in units of kW/ton.

The heat rejection load on the tower is

$$LOAD = \left[\sum^{\substack{\text{number of} \\ \text{watercooled} \\ \text{chillers}}} \text{chiller heat rejection} \right] + EXTRA + (EPUMP * EFMOT).$$

Here, it is assumed that only the shaft energy of the condenser pump heats the water, the rest of the pump energy is dissipated to the air.

If the TOWER subroutine has been called only to guess the tower temperature (the tower didn't run the hour before), the steps above are skipped. Instead, the load and flow rate are guessed so that the simulation may calculate the temperature. The load is guessed to be

$$LOAD = \frac{PDEM}{CAPCLR} * DESLD,$$

where PDEM is the cooling load from the SYSTEMS program. CAPCLR is the sum of the capacities of all the chillers, and DESLD is the total heat rejection capacity of all the chillers. The water flow rate is likewise guessed to be

$$GPM = \frac{PDEM}{CAPCLR} * DESGPM,$$

where DESGPM is the sum of the water flow rates of all the chillers.

<u>Step 2. The minimum number of cells</u> that can handle the water flow rate is

$$MINCELL = \frac{GPM}{GPMMAX} .$$

Step 3. The range (temperature drop) for the given LOAD and GPM is

$$RANGE = \frac{LOAD}{(GPM * 8.341\ lb/gal * 60\ min/hr)} .$$

Step 4. Set the tower exit water temperature.

The user has the option to input the tower temperature control (keyword TWR-TEMP-CONTROL) as either FLOAT or FIXED. If the default FLOAT is chosen, the water exit temperature is assumed to be 5°F above the wet-bulb temperature (approach of 5°F). If FIXED, the exit temperature is at the tower water temperature set point (keyword TWR-WTR-SET-POINT) corrected by the throttling range (keyword TWR-WTR-THROTTLE). The program first assumes the control temperature can be reached.

If keyword TWR-TEMP-CONTROL = FLOAT, then TTOWR = TWET + 5.0. (5°F is the closest approach for which the curves are acceptable, except for the strainer cycle, which allows the limit to be 2°F).

For the direct cooling THERMO-CYCLE mode (uses the chiller as a heat exchanger),

$$TTOWR = TWET + \left[1.7 + \frac{(6.7) * (PDEM)}{DESLD}\right]$$

for PDEM larger than 5 per cent. PDEM is the cooling load calculated by SYSTEMS for this hour. DESLD is the maximum expected load.

If keyword TWR-TEMP-CONTROL = FIXED, then

$$TTOWR = TSET + \left[THROTL\left(\frac{RANGE}{RNGNOM} - 0.5\right)\right],$$

where TSET is the cooling tower temperature set point, THROTL is the temperature throttling range, and RNGNOM is the design temperature drop of the cooling tower.

For the direct cooling STRAINER-CYCLE mode

TSET = CHWT.

In either case, TTOWR must be at least the minimum allowable cooling tower temperature (input by keyword MIN-TWR-WTR-T for normal cooling, 36°F for strainer cycle).

Step 5. Determine the approach for TTOWR from Step 4

APP = TTOWR - TWET.

The wet-bulb temperature, TWET, is not allowed to be less than 55°F (30°F for strainer cycle) or greater than 85°F.

Step 6. Set the fan speed.

If this is the first guess at the speed, ISPEED = OFF (natural convection). If this speed is too low to produce the needed cooling, the speed will be reset later to either LOW or HIGH, depending on the value of TWR-FAN-CONTROL.

Step 7. Determine the rating factor for the RANGE, APP, and ISPEED calculated above as follows:

$$RF = 10^{(R1 + R2)} * CFMCOR_{ISPEED}, \tag{V.4}$$

where $R1 = f_1(RANGE,TWET)$, and $R2 = f_2(APP,TWET)$. f_1 and f_2 are bi-linear or bi-quadratic expressions corresponding to keywords TWR-RFACT-FRT and TWR-RFACT-FACT respectively.

$CFMCOR_{ISPEED}$ was precalculated in the TOWERD design subroutine.

See Sec. V.2.2.3.6.1 for an explanation of these functions.

Step 8. Determine the tower area needed and number of cells.

AREA = GPM * RF

$$NCELL = \frac{AREA}{ARCELL} \text{ rounded up.}$$

If NCELL is greater than the maximum number available (specified by keyword MAX-NUMBER-AVAIL), then the fans must operate at a higher speed and steps 6, 7, and 8 are repeated. If NCELL is still too large when the fans are on high, then the assumed approach is too low and the water temperature is floating above the control temperature.

Step 9. The water temperature is floating. The water flow rate has been set by the chillers, and the fans must be at full speed if the temperature is floating above the set point. The rating factor is by definition

$$RF = \frac{ARCELL * MAX\text{-}NUMBER\text{-}AVAIL}{GPM} .$$

The range has been set by the chillers (heat rejection/lbs water flow) and the wet-bulb temperature is known. Therefore, R1 = f(RANGE, TWET) is fixed. R2 must be

$$R2 = \log_{10}(RF) - R1.$$

The required approach can now be found by an equation fitted to the performance charts

$$APP = f(R2, TWET),$$

where f is the inverse of f_2 (step 7) and corresponds to keyword TWR-APP-FRFACT.

R2 in the above expression is not allowed to be less than -0.6, which roughly corresponds to an approach of 30°F.

The tower temperature is then TTOWR = TWET + APP.

Step 10. Determine Total Power Required.

Fan Energy - If the exit temperature is floating above the control point, the fan energy is simply

$$EFAN = EFCELL * MAX\text{-}NUMBER\text{-}AVAIL,$$

where EFCELL is the fan energy per cell at high speed (precalculated in the design routine).

If the exit temperature is at the control point, the fans are probably cycling between two speeds. If the fans remain on the higher speed, the exit temperature will be too low. If the fans remain on the lower speed, the exit temperature will be too high. The fraction of the hour that the fan is on the higher speed is approximated as a function of the area needed at the lower speed (ARLOW), the actual area (ARCELL * NCELL), and the area needed at the higher speed (AREA),

$$FRAC = \frac{ARLOW - (ARCELL * NCELL)}{ARLOW - AREA} .$$

The power is then equal to the power at each fan speed multiplied by the fraction of time at each speed.

The total electrical energy used is the sum of the fan and pump energy

ELEC = EFAN + EPUMP.

2.2.3.6.4 Simulation Limitations

1. The cooling tower is simulated to account for its electrical consumption and to predict the leaving tower water temperature. The leaving tower water temperature is used in the chiller algorithms to adjust their design capacities and electrical consumption for off-design performance. To simulate the tower, the chiller heat rejection loads must be known. But to simulate the chillers, the leaving tower water temperature must be known. The most accurate way to solve this problem would be to iterate until the chiller heat rejection loads and the tower temperature converged. A second approach would be to use the tower temperature from the previous hour in the chiller simulation. This method will work fairly well if the wet-bulb temperature changes relatively slowly from hour to hour and if the chillers are not strongly sensitive to the tower temperature. The advantage of this apprcach is the computer time saved by not having to iterate, and the simplified code.

   The second approach is the method used in DOE-2.1. The chiller simulation uses the tower temperature from the hour before. If the tower did not operate during the previous hour, the TOWER subroutine is called so that the water temperature may be guessed. This approach is felt to be sufficiently accurate so that the iterative method is not necessary.

2. The user is advised to allow the program to size the tower. Unlike the other PLANT-EQUIPMENT types, MAX-NUMBER-AVAIL is disregarded when the program sizes the tower, i.e., the program sets the number of cells.

3. The TOWER subroutine will not simulate wet-bulb temperatures below 55°F. If the wet-bulb temperature is below 55°F, it will be reset to 55°F. If a strainer cycle is being simulated, the minimum temperature is 30°F.

2.2.4 Hot and Cold Storage Tanks (subroutines STORJD and STORAJ)

This algorithm simulates hot water and cold water storage tanks. The PLANT program has no capability of operating the tanks in a default mode; the storage and use of energy in the tanks is controlled by the user. Storage is accomplished through the use of the appropriate schedule entered under the ENERGY-STORAGE command. The tanks are used through the LOAD-ASSIGNMENT command. The more common uses of the tanks include:

1. storage of energy for use during peak periods, thus allowing the capacity of equipment to be reduced,

2. unloading equipment and using the stored energy during the times of peak electrical loads, and

3. using the hot tank to store excess recoverable waste heat for use at later times.

The cold water tank is used in a manner similar to the chillers to satisfy space cooling loads. The use of the hot tank is a little more complicated because heating demands may be from space heating, domestic/process hot water heating, absorption chillers, and steam turbines. Obviously, a hot water tank cannot actually meet any loads that require steam, such as loads from two-stage absorption cooling, steam turbines, and possibly space heating. The user specifies which heating loads the hot tank is to be used for by specifying the tank as a supply in a HEAT-RECOVERY link. The tank will supply heat only to the demands it is linked to. The links are entirely up to the user; the program doesn't check to see whether a load from the space heating system uses steam or hot water; it simply supplies Btu's.

The hot tank also differs from the cold tank in the way it is charged. A cold tank is charged from chillers, whereas a hot tank can be charged from boilers or with recovered heat (the tank will store recovered heat if input as a demand on a HEAT-RECOVERY level). This difference shows up in the charging schedules. The cold tank charging schedule will always force chillers to operate when charging. The hot tank charging schedule is more flexible. It will allow the tank to charge itself "passively" by only taking available recoverable heat, or "actively" by forcing boilers to operate.

The algorithm simulates storage tank heat losses as a U-value times Area product multiplied by the difference between the tank temperature and the environmental temperature. The temperature of the environment can be either the outside ambient temperature or a constant temperature.

Hysteresis is built into the storage controls. Once a tank is fully charged, it will not allow itself to charge again until at least 10 percent of its capacity is used up, either by satisfying heating or cooling demands or through losses. This is done to prevent the tank from charging at very low rates, thereby forcing the equipment charging the tank to operate very inefficiently. For example, a fully charged hot tank may need a very small amount of heat each hour because of conduction losses. A boiler forced to operate every hour simply to replace this small loss would operate very inefficiently. The hysteresis allows the losses to accumulate until 10 percent of the tank's capacity has been lost. Then the tank will allow itself to be recharged if the charging schedule allows it. The hysteresis rule applies only when the tank is charging from the boiler or chiller, not from heat recovered in the heat-recovery algorithm.

The storage tank algorithm is based on Btu's of energy stored, lost, used, and needed. The algorithm calculates the tank temperatures each hour only to calculate the conduction losses and to see if the tank is freezing. Basing the simulation on Btu's rather than temperatures allows both fully stratified and fully mixed tanks to be simulated by the same algorithm. For the purposes of simulation, the only difference between the two types of tanks is that a stratified hot tank can have a lower base temperature (higher if a cold tank) and a greater temperature range. This idea will be discussed in more detail following the presentation of the algorithm. It should be mentioned here that the algorithm is not capable of simulating a stratified tank whose temperature gradient decays with time.

With the exception of heat recovery, the hot tank is simulated identically to the cold tank. The algorithm for the hot tank is presented here. The keywords mentioned will apply to the cold tank if HTANK- is replaced by CTANK-.

Keyword	FORTRAN Variables	Engineering Variables	Description
		ADJUST	the amount the supply and demand of the tank are adjusted to prevent the tank from supplying its own demand.
		BASEHT	the heat content of the tank at the base temperature.
		EHSTOR	the useful heat in the tank.
ELEC-INPUT-RATIO		EIR_{19}	the electric input ratio for the tank.
HTANK-BASE-T		HBASET	the tank temperature below which there is no useful heat stored.
		HFREEZ	the amount of heat needed to keep the tank from freezing.
		HLOSS	the heat lost to the environment.
HEAT-STORE-RATE		HSTRRT	the rate energy is stored in the tank.
HEAT-SUPPLY-RATE		HSUPRT	the rate energy is withdrawn from the tank.
		$HTAVAL_{19}$	the energy available from the tank this hour.
		HTASK	the amount of heat requested by the tank this hour.
		HTFILL	the remaining unfilled storage capacity.
		HBTU	storage tank heat capacity (Btu/°F).
HTANK-LOSS-COEF		HCOEF	the heat loss coefficient (Btu/hr).
HTANK-T-RANGE CTANK-T-RANGE		HDT	the temperature range in which the tank will store heat.
		HELECP	hourly tank pump energy consumption.
		HTGIVE	the amount of heat the tank can give this hour.

Keyword	FORTRAN Variables	Engineering Variables	Description
HEAT-SUPPLY-RATE		HTON	90 percent of storage tank capacity. The tank will not start charging unless the stored heat is less than this value.
		HTREQ19	the amount of heat needed by the tank before any storage of recovered heat.
		$HTRQ_{19}$	the initial amount of heat needed by the tank when subroutine PIPES is called.
		LOAD	the heating demand.
		REALHT	the hourly heat content of the tank.
		REMAIN	the portion of the heating load that has not been allocated.
		STORED	the amount of heat stored in the tank this hour.
		TAIR	outside air temperature.
		TEMPH	the hourly tank temperature.
HTANK-ENV-T		TENVH	a user-supplied constant environmental temperature surrounding the tank.
HTANK-FREEZ-T		TFREZH	the freezing point of the tank fluid.
		$TOTCAP_{19}$	the heat storage capacity of the tank.
		TOUT	the temperature of the air surrounding the tank.

2.2.4.1 Design Calculations (subroutine STORJD)

The design calculations are done at the beginning of the simulation in routine STORJD. The use of the variables calculated here will become clear in the hourly calculations.

The tank heat capacity, or thermal capacitance (Btu/°F) is

$$HBTU = \frac{TOTCAP_{19}}{HDT} \qquad (V.5)$$

where $TOTCAP_{19}$ is the heat storage capacity of the tank and HDT is the temperature range in which the tank will store heat. HDT corresponds to the keyword HTANK-T-RANGE.

The heat content of the tank (Btu, relative to 0°F) at the base temperature is

$$BASEHT = HBTU * HBASET. \tag{V.6}$$

HBASET is the tank temperature below which there is no useful heat stored. HBASET corresponds to the keyword HTANK-BASE-T.

The hourly heat content of the tank (Btu, relative to 0°F) is initially set to the base heat content, i.e., no useful heat initially

$$REALHT = BASEHT. \tag{V.7}$$

The tank will not start charging unless less than 90 percent of its useful storage capacity remains

$$HTON = TOTCAP_{19} * .9. \tag{V.8}$$

The energy consumed hourly by the tank pump is determined by the larger of the maximum heat storage rate or maximum supply rate

$$HELECP = EIR_{19} * \begin{bmatrix} HSTRRT \\ \text{or} \\ HSUPRT \end{bmatrix}. \tag{V.9}$$

HSTRRT and HSUPRT correspond to the keywords HEAT-STORE-RATE and HEAT-SUPPLY-RATE respectively. EIR_{19} corresponds to the keyword ELEC-INPUT-RATIO. Note that the default for EIR_{19} is 0.

The tank algorithm is capable of simulating only one hot tank and/or one cold tank. If the user inputs more than one of each tank, the algorithm will issue a warning and treat them as one tank.

2.2.4.2 Hourly Simulation (subroutine STORAJ)

The hourly simulation for the storage tanks is done in the routines STORAJ and EQUIP. In addition, part of the simulation for the hot tank only is done is PIPES. The simulation is done in the following order: (1) STORAJ, the main storage tank routine, determines how much heat the tank can supply and, if allowed, how much heat the tank can store; (2) PIPES, the heat recovery routine, simulates the supply and demand linkages of the hot tank; (3) EQUIP, the load assignment processor, determines how much energy the tanks supply or how much energy they store; (4) STORAJ updates the heat stored in the tanks and sets the electrical consumption of the pumps.

Step 1. Determine heat supply and/or storage.

The temperature of the environment surrounding the tank is either

$$\text{TOUT} = \text{TAIR} \tag{V.10a}$$

or

$$\text{TOUT} = \text{TENVH}. \tag{V.10b}$$

The default choice, Eq. (V.10a), is the outside air temperature, TAIR. If the user input a constant environmental temperature, TENVH (keyword HTANK-ENV-T), then Eq. (V.10b) is used.

The tank temperature (°F) is

$$\text{TEMPH} = \frac{\text{REALHT}}{\text{HBTU}} \tag{V.11}$$

where REALHT and HBTU, defined in Eqs. (V.5) and (V.7), are the heat content of the tank (Btu relative to 0°F) and tank heat capacity (Btu/°F) respectively.

The heat lost to the environment in the last hour is

$$\text{HLOSS} = \text{HCOEF} * (\text{TEMPH} - \text{TOUT}). \tag{V.12}$$

HCOEF is heat loss coefficient (Btu/hr-°F) and corresponds to the keyword HTANK-LOSS-COEF.

The Btu heat content and temperature of the tank is adjusted by the loss

$$\text{REALHT} = \text{REALHT} - \text{HLOSS} \tag{V.13}$$

$$\text{TEMPH} = \text{REALHT/HBTU}. \tag{V.14}$$

If the tank temperature is less than the fluid freezing point, the tank must receive enough heat to keep it from freezing, regardless of whether or not the charging schedule is on. The amount of heat needed is

$$\text{HFREEZ} = (\text{TFREZH} - \text{TEMPH}) * \text{HBTU}. \tag{V.15}$$

TFREZH is the fluid freezing point and corresponds to the keyword HTANK-FREEZ-T.

The useful heat in the tank is the portion greater than the heat present at the base temperature

$$EHSTOR = REALHT - BASEHT, \tag{V.15a}$$

where BASEHT was defined in Eq. (V.6).

The remaining unfilled storage capacity is

$$HTFILL = TOTCAP_{19} - EHSTOR \tag{V.16}$$

where $TOTCAP_{19}$ is the maximum storage capacity of the tank.

If the tank is allowed to charge this hour, the amount of heat requested is

$$HTASK = HSTRRT \text{ or } HTFILL, \text{ whichever is smaller.} \tag{V.17}$$

HSTRRT is the maximum charging rate and corresponds to the keyword HEAT-STORE-RATE. It was mentioned previously that the tank will not start charging unless 10 percent or more of its capacity is unfilled and the charging schedule allows it. This condition corresponds to EHSTOR $<$ HTON, where HTON was defined in Eq. (V.8). Once the tank starts charging, it will continue to charge over the hours until EHSTOR = $TOTCAP_{19}$, or until the schedule turns it off.

The amount of heat the tank can give this hour is

$$HTGIVE = HSUPRT \text{ or } EHSTOR, \text{ whichever is smaller.} \tag{V.18}$$

HSUPRT is the maximum supply rate and corresponds to the keyword HEAT-SUPPLY-RATE.

The heat quantities the tank can supply and store are placed in the plant heat supply and demand arrays

$$HTAVAL_{19} = HTGIVE \tag{V.19}$$

$$HTREQD_{19} = HTASK. \tag{V.20}$$

Step 2. Simulate the supply and demand linkages.

The cold tank simulation skips this step and goes directly to the LOAD-ASSIGNMENT processor.

Routine PIPES processes the HEAT-RECOVERY command (Sec. V.2.2.5). Its purpose in simulating a hot tank is twofold:

1. to calculate how much energy can be stored from recoverable heat and from the boilers, and

2. to calculate how much heat the tank can supply to the demands it is linked to assuming the LOAD-ASSIGNMENT processor (Routine EQUIP) calls upon the tank for its heat. The LOAD-ASSIGNMENT processor is called upon after PIPES is called, so PIPES does not know whether the hot tank will actually be used. PIPES tells the LOAD-ASSIGNMENT processor how much heat the tank could supply to its demands if it was turned on.

The amount of heat needed by the tank before any storage of recovered heat is $HTREQD_{19}$ [Eq. (V.20)]. This initial value is saved at the beginning of PIPES

$$HTRQ19 = HTREQD_{19}. \tag{V.21}$$

PIPES then loops through the heat recovery levels and decreases $HTREQD_{19}$ by any available supplies it is linked to. The amount stored in the tank is then

$$STORED = HTRQ19 - HTREQD_{19}. \tag{V.22}$$

At this point, $HTREQD_{19}$ is the decreased amount of heat still requested by the tank after the storage of recovered heat. If the charging schedule is in the "active" mode (-1 entered for this hour in schedule), $HTREQD_{19}$ will be passed on to the boiler. If the charging schedule is in the "passive" mode, (1 entered for this hour in the schedule), only the recovered heat will be stored, and $HTREQD_{19}$ will be zeroed. If the tank needs heat to keep from freezing and STORED < HFREEZ, the difference will be passed on to the boilers.

PIPES stores the amount of heat the tank can supply to the demands it is linked to (assuming it has been turned on) in $HTGAVE_{19}$. The energy available from the tank, $HTAVAL_{19}$, is reset to $HTGAVE_{19}$. $HTAVAL_{19}$ will be used in the LOAD-ASSIGNMENT processor to allocate a load to the tank [Eq. (V.23)].

Step 3. Load Assignment.

The LOAD-ASSIGNMENT processor (subroutine EQUIP, Sec. V.2.2.8) allocates loads to be met by storage tanks in a manner similar to the way it allocates loads to other equipment types, with a few exceptions:

1. The capacity of the tank is not the size of the tank as it is with other equipment types; rather it is the energy available for use this hour, $HTAVAL_{19}$, calculated in Eq. (V.19) and the above paragraph.

2. The tank should not supply its own demand for energy. If the tank is called upon to supply energy, the routine first checks to see if the tank is also requesting energy ($HTREQD_{19} > 0$). If it is, then both the requested supply and demand of the tank are adjusted so that one of them is zero

$$ADJUST = REMAIN \text{ or } HTREQD_{19}, \text{ whichever is smaller.} \tag{V.23a}$$

$$LOAD = LOAD - ADJUST \tag{V.23b}$$

$$REMAIN = REMAIN - ADJUST \tag{V.23c}$$

$$HTREQD_{19} = HTREQD_{19} - ADJUST. \tag{V.23d}$$

LOAD is the heating demand to be allocated to equipment and REMAIN is the portion of LOAD that hasn't been allocated yet. Because other heating equipment may have been assigned loads before the tank, the storage request from the tank may already be partially met. In this case, the remaining load, REMAIN, will be smaller than the original storage request, $HTREQD_{19}$. ADJUST is then the portion of the storage request that will not be satisifed.

3. Once the routine has allocated loads to the equipment, it checks to see if there is any unallocated load remaining. If there is, i.e., there is an overload, it checks to see if there is a storage demand from the tank contributing to the overload. If there is, both the storage demand and the overload are adjusted so that one of them is zero

$$ADJUST = REMAIN \text{ or } HTREQD_{19}, \text{ whichever is smaller.} \tag{V.24a}$$

$$LOAD = LOAD - ADJUST \tag{V.24b}$$

$$HTREQD_{19} = HTREQD_{19} - ADJUST \tag{V.24c}$$

where REMAIN is the overload.

$HTREQD_{19}$ has changed its meaning several times in being processed through the routines. Originally, it was the heat requested to charge the tank. In the heat recovery algorithm, it was diminished by the amount of recovered heat, STORED. In the LOAD-ASSIGNMENT algorithm, the charging request can again be diminished, either because the request would force the tank to charge itself, or because charging the tank would cause an equipment overload.

This equation is a little ambiguous in the code. $HTREQD_{19}$ and STORED are stored in $EQDEM_{4,19}$ and "the amount used" is stored in $EQDEM_{1,19}$, when the EQDEM array is simply a record keeping convenience. Equation (V.25) is then

$$REALHT = REALHT + EQDEM_{4,19} + EQDEM_{1,19}.$$

The final meaning of $HTREQD_{19}$ is the energy the tank receives from the boilers, exclusive of any recovered energy.

Step 4. Adjust heat in tank for hourly activity.

Routine STORAJ is called once again at the end of the hourly simulation. It adjusts the total amount of heat in the tank for any that was stored or used

$$REALHT = REALHT + HTREQD_{19} + STORED - (\text{the amount used}). \qquad (V.25)$$

It also sets the electricity consumed by the pump. The pump is assumed to operate any time the tank stores or gives out heat

$$HELEC = HELECP,$$

where HELECP was defined in Eq. (V.9).

As previously stated, the algorithm for the cold tank is identical to the hot tank algorithm, except that the section of the HEAT-RECOVERY calculations is skipped.

2.2.5 Heat Recovery (subroutines PIPESD and PIPES)

The heat recovery algorithm links user-specified sources of waste heat to user-specified equipment or processes that need heat. In general, no heat recovery equipment is assumed to exist unless the user defines the linkage in the HEAT-RECOVERY command. The exception to this rule is that by default, a link will be provided between the rejected heat of double bundle chillers and space heating demands.

The algorithm assumes that the temperature differences between the heat supplies and demands are great enough so that the necessary amount of heat can be transferred. In most cases, the program does not do a heat transfer calculation using temperatures and heat-exchange UA products to calculate the heat transferred. For example, assume the diesel engine generator algorithm calculates that 500,000 MBtu of heat can be recovered from the diesel water jackets. When calculating this heat quantity, the diesel algorithm does not know whether the heat will be used for low temperature space heating or higher temperature two-stage absorption cooling. It only knows that the diesel engine should be maintained at a constant temperature and 500,000 MBtu's of heat will have to be removed from the jacket to do so. This heat can either be recovered for some purpose or it can be rejected to the environment. In either case, 500,000 MBtu of jacket heat will be disposed of. Because of this insensitivity to temperature, the user is advised to use the heat recovery linkage with caution. It would be unrealistic to power a steam turbine with the steam from a diesel water jacket.

The exception to the general rule discussed above occurs when recovering heat from the exhaust of a diesel or gas turbine generator. These two algorithms use the temperature of the hot exhaust gases, the steam saturation temperature, and the exchange UA product to calculate the recoverable heat. The diesel and gas turbine algorithms (Sec. V.2.2.7) describe this in more detail.

Keyword	FORTRAN Variables	Engineering Variables	Description
	DBLEFT	DBLEFT	the unused double bundle chiller heat.
	DEMAND	DEMAND	the demand at a given level of heat recovery.
	EBOILR	EBOILR	the heating load passed on to the boiler.
	ERECVR	ERECVR	the total amount of heat recovered.
	EREJ	EREJ	the wasted recoverable heat.
	EXTSOL	EXTSOL	the sum of the solar energy supplied through the three solar heating supplies.
		GIVE	the amount of a supply that is not yet allocated to a demand.
	HTAVAL	$HTAVAL_i$	the hourly heat supply of each equipment type or process.
	HTGAVE	$HTGAVE_i$	the heat given this hour by the ith supply.
	HTGETT	$HTGETT_i$	the total amount of heat recovered by the ith demand.
	HTREQD	$HTREQD_i$	the hourly heat demand of each equipment type or process.
	SUPPLY	SUPPLY	the hourly heat given by a supply at a giver level of heat recovery.
	TAKE	TAKE	the amount of the available heat that is "taken" by a demand at a given level.

2.2.5.1 Design Calculations (subroutine PIPESD)

Subroutine PIPESD sets up the hourly heat recovery at the beginning of the simulation. The algorithm first determines how many levels* of heat recovery links have been input. Then it examines the links and flags the pieces of equipment that will be supplying heat. For example, the diesel algorithm will not calculate how much heat is available from the diesel water jacket unless this heat is to be used. The algorithm also sets a flag so that the double bundle chiller algorithm will know if it is hooked up to a hot storage tank. If it is, it will operate in the heat recovery mode whenever the tank is requesting heat.

The rest of the design algorithm checks for errors and suspicious linkages in the users input. Depending on the nature of the problem, the program may fix it, issue a warning, or issue an error statement and abort. The checks are summarized below.

Violations of the Second Law of Thermodynamics

If the algorithm detects a supply-demand link whose temperatures look suspicious, it will print a warning. For example, the algorithm will allow a two-stage absorption chiller to be powered by the waste heat of a double bundle chiller. It finds this link highly suspicious, however, and will print a warning to alert the user.

Illegal equipment

There are some types of links that are illegitimate. For example, a double bundle chiller can be a supply of heat, but it cannot be a demand. This is a non-fatal error and the algorithm simply issues a warning if it detects one. A link is also considered to be illegitimate if it uses a type of equipment that was never defined in a PLANT-EQUIPMENT instruction.

Multiple solar links

The heat recovery algorithm cannot simulate more than one solar supply at any given level (they can be simulated if on different levels). The algorithm will print an error message and abort.

Hot storage tank

In almost all cases, the user will want the tank to supply heat only when no other recoverable heat is available. Similarly, the user will probably want the tank to store recoverable heat only if there is no other unsatisfied demand for the heat. As a result, the program must do several checks on the hot tank links.

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* The heat recovery level indicates the relative temperature of the sources of recoverable heat and its associated demand. This allows the highest temperature sources to be assigned to the demands that require the highest temperatures. Table V.11 of the DOE-2 Reference Manual (Ref. 2) presents a temperature hierarchy that compares the temperatures of various supplies and demands. Up to five levels of recoverable heat supply and demand are permitted.

a. If the tank has been defined in a PLANT-EQUIPMENT command but not defined as a supply in the HEAT-RECOVERY command, the program will abort.

b. The tank must be last in the list of supplies at any level. If is is not the list will be rearranged so that the tank is the last supply at that level.

c. The tank demand must be on a level with no other demands. If it is not, the tank demand and its supplies will be moved to an empty level if one exists. Otherwise, the program will abort.

d. The demands hooked to a tank supply cannot be re-entered again at a following level. (They can be entered at an earlier level with no problem.) If they are, a message will be printed and the program will abort.

Checks b and c above were written to allow compatibility between the heat recovery input of DOE-2.0A and DOE-2.1

2.2.5.2 Hourly Simulation (subroutine PIPES)

The heat recovery linkages are simulated hourly in subroutine PIPES. This algorithm links any user-specified heat demands to any user-specified heat supplies. Any unmet demands are passed on to the appropriate heating equipment. The algorithm loops down through the levels, satisfying the SUPPLY-1 to DEMAND-1 lists before satisfying the SUPPLY-2 to DEMAND-2 lists, etc. The supplies and demands at each level give and receive heat sequentially; the first supply listed at a level is used before the second, and the second before the third.

The first demand at a level receives the supplies before the second, and the second before the third. The demands are decreased by the amount of heat given by the supplies, and the supplies are likewise decreased by the heat given to the demands. The demands left after all the recovery levels have been processed are the loads the heating equipment must meet. The total amount of heat given by each supply through the entire run is reported as recovered heat. The unused supplies are reported as wasted recoverable heat. Wasted recoverable heat includes only supplies that are being used in heat recovery. If DIESEL-JACKET is not input as a supply, then its potential heat is not counted as wasted, it is simply ignored.

The hourly supplies and demands of each equipment type or process are stored in the arrays $HTAVAL_i$ and $HTREQD_i$ respectively. The subscript i refers to the particular equipment type or process in question. Only the supplies input by the user are stored in HTAVAL. All of the heat demands, whether used in heat recovery or not, are stored in HTREQD.

The recoverable heat supplies, $HTAVAL_i$, and the heating demands of equipment and processes, $HTREQD_i$, are calculated in the algorithm simulating that equipment type or process. The exceptions are the supplies from the solar storage tank, the heat recoverable from boiler blowdown, and the heat required for boiler makeup water. These are calculated in the heat recovery algorithm, although they are discussed in the writeups of the boiler and plant-solar interface.

If there is no heat recovery to be accomplished, i.e., the user did not specify any links in the HEAT-RECOVERY command and there is no double bundle chiller, the algorithm skips Eqs. (V.26) through (V.37) and simply calculates the load on the heating equipment in Eq. (V.38).

The demand at a given level of heat recovery is

$$DEMAND = \sum HTREQD_i \tag{V.26}$$

where the subscript i refers to the demands input at this level.

The heat given by a supply at this level is

$$SUPPLY = HTAVAL_i \text{ or } DEMAND\text{, whichever is smaller.} \tag{V.27}$$

An intermediate variable, GIVE, is used to keep track of how much of the SUPPLY is as yet unallocated. Initially,

$$GIVE = SUPPLY. \tag{V.28}$$

The demands at this level TAKE from the SUPPLY (the unallocated SUPPLY is GIVE) in the order the demands are listed

$$TAKE = HTREQD_i \text{ or } GIVE\text{, whichever is smaller.} \tag{V.29}$$

This demand and the remaining supply are decreased by the amount taken

$$HTREQD_i = HTREQD_i - TAKE \tag{V.30}$$

and

$$GIVE = GIVE - TAKE. \tag{V.31}$$

The total amount of heat recovered by a given demand is stored for use in the BEPS report

$$HTGETT_i = HTGETT_i + TAKE. \tag{V.32}$$

Equations (V.29) through (V.32) are repeated for each demand at this level. The heat still available from the supply is incremented (reduced) by the amount taken at this level

$$HTAVAL_i = HTAVAL_i - SUPPLY. \tag{V.33}$$

The heat given this hour by this supply is incremented (increased)

$$HTGAVE_i = HTGAVE_i + SUPPLY. \tag{V.34}$$

The demand still left at this level after this supply is

$$DEMAND = DEMAND - SUPPLY. \tag{V.35}$$

Equations (V.27) through (V.35) are repeated for each supply at a given level. Equations (V.26) through (V.35) are repeated for each level of heat recovery.

Equation (V.33) is done slightly differently if the supply is from the solar storage tank. The user can specify up to three solar supplies: SOL-SPACE-HEAT, SOL-PROCESS-HEAT, and SOL-COOLING. All three of these supplies come from the same storage tank, the only difference being the minimum temperature at which each supply is useful. As a result, any time heat is taken from the solar storage tank through any one solar supply, the $HTAVAL_i$ corresponding to each of the three solar supplies must all be decreased.

Equations (V.28) through (V.32) are skipped if the supply is from the hot storage tank. The reason is developed fully in the storage tank writeup, but briefly is as follows: The storage tank is considered to be a piece of heating equipment and is not allocated a load by the LOAD-ASSIGNMENT algorithm until after all heat recovery has been accomplished. The heat recovery algorithm does not know whether the tank is actually turned on. Its purpose is to let the LOAD-ASSIGNMENT algorithm know how much heat the tank could supply if it was turned on. Therefore, demands that might be satisfied by the tank cannot be adjusted any more once their links to the tank have been encountered. This is the reason that demands linked to the tank cannot be linked to another supply after the tank link.

Once Eqs. (V.26) through (V.35) have been repeated for all the levels of links, the amount of heat recovered is

$$ERECVR = \sum HTGAVE_i. \tag{V.36}$$

$HTGAVE_{19}$ corresponding to the storage tank is not included in the summation because it isn't known whether the tank is really operating. Solar heat linked through HEAT-RECOVERY is considered to be "recovered" for the purposes of report PS-A, but is reported separately in the BEPS report.

The wasted recoverable heat is the sum of the unused supplies

$$EREJ = \sum HTAVAL_i. \tag{V.37}$$

The heating load passed on to the boilers is the sum of the remaining demands

$$EBOILR = \sum HTREQD_i. \tag{V.38}$$

If a FURNACE has been defined, $HTREQD_{25}$ (the remaining space heating load) is passed directly to the furnace algorithm and is not included in EBOILR. The same applies for domestic water heating loads ($HTREQD_{26}$) when domestic water heaters have been defined.

The three solar heating supplies used in the heat recovery links are summed for the solar simulator.

$$EXTSOL = \sum_{i}^{\text{solar indexes}} HTGAVE_i. \tag{V.39}$$

Finally, the unused double bundle chiller heat is passed to the next hour's cooling tower simulation

$$DBLEFT = HTAVAL_{12}.$$

2.2.6 Space Heating and Cooling Distribution Systems (subroutine PUMPSD)

This algorithm simulates the pumps and distribution losses of the heating and cooling distribution pipes. The design calculations for the pumps and losses are performed in routine PUMPSD. The hourly accounting of losses and electrical consumption is done in the main PLANT subroutine. Heating distribution duct losses for a furnace were previously calculated in the SYSTEMS simulation.

The pumps are not explicitly defined by the user through a PLANT-EQUIPMENT command. The program defines pumps when they are needed. A chilled water pump is defined whenever SYSTEMS has chilled water coils indicated. A hot water pump is defined whenever SYSTEMS has hot water coils. A hot water pump is not defined if a steam boiler or forced air furnace is input because these types of equipment are not normally used with hot water coils. The pumps are modeled as constant volume pumps whose electrical consumption is independent of the loads in the distribution system. Operation of the hot and cold pumps is controlled by the BOILER-CONTROL and CHILLER-CONTROL keywords in a manner similar to the operation of the boilers and chillers. The pumps will normally operate only when there is a heating or cooling load from SYSTEMS. In the STANDBY mode of operation, the heating and/or cooling pump(s) will operate any time heating and/or cooling is scheduled to be available in SYSTEMS, even when there is no load.

The distribution losses are calculated as a fraction of the design heating and/or cooling loads incurred in SYSTEMS. They are calculated only for the hours the circulation pumps operate and are assumed to be independent of the loads and environmental temperatures.

The design calculations for the hot water pump energy and distribution losses are presented below. The chilled water calculations are identical in form and are not presented.

Variable List:

Keyword	FORTRAN Variables	Engineering Variables	Description
	GPM	GPM	the water flow rate through the distribution piping.
HCIRC-DESIGN-T-DROP	HDESDT	HDESDT	the design temperature drop through the system.
HCIRC-IMPELLER-EFF	HEFFI	HEFFI	the circulation pump impeller efficiency.
HCIRC-MOTOR-EFF	HEFFM	HEFFM	the circulation pump motor efficiency.
	HHGAIN	HHGAIN	the hourly heat loss or gain from the distribution piping.
HCIRC-LOSS	HLOSS	HLOSS	the fraction of the design space heating load that is lost.
	HPELEC	HPELEC	the electric power consumed hourly.
HCIRC-HEAD	HPHEAD	HPHEAD	the pressure head across the circulation pump.
	HTSUM	HTSUM	the peak space heating load from SYSTEMS.

The water flow rate through the space heating distribution piping is

$$GPM = \frac{(HTSUM)}{[HDESDT * 8.341 \text{ lb/gal} * 60 \text{ min/hr} * 1.0 \text{ Btu/lb-}^{\circ}\text{F}]},$$

where HTSUM is the peak space heating load from SYSTEMS (Btu/hr), HDESDT is the design temperature drop (°F) through the system and can be input through the keyword HCIRC-DESIGN-T-DROP.

The electrical power consumed hourly is

$$HPELEC = \left(\frac{HPHEAD * GPM}{HEFFM * HEFFI}\right) * .643 \frac{\text{Btu-minute}}{\text{ft-gallons-hr}}$$

where HPHEAD is the pressure head across the pump, HEFFM is the pump motor efficiency, and HEFFI is the pump impeller efficiency. They can be input through the keywords HCIRC-HEAD, HCIRC-MOTOR-EFF, and HCIRC-IMPELLER-EFF respectively.

The hourly heat loss or gain is calculated as a fraction of the design space heating load

$$HHGAIN = HTSUM * HLOSS,$$

where HLOSS is the fraction of the design space heating load and can be input through the keyword HCIRC-LOSS. The loss is diminished somewhat by the pump energy that heats the loop

$$HHGAIN = HHGAIN - (HPELEC * HEFFM).$$

Here it is assumed that the pump motor is ventilated and that only the shaft energy heats the water.

The algorithm for the chilled water pump is identical except that the pump heating effect increases the loss rather than decreases the loss as is the case for the hot pump.

2.2.7 Electrical Equipment

Diesel and gas turbine generator simulations are described in this section.

Variable List:

Keywords	FORTRAN Variables	Engineering Variables	Description
	CAP	CAP	the design (rated) capacity of the diesel generators operating this hour.
	EELEC	EELEC	the electrical load on the gas turbines.
	EELECD	EELECD	the electrical load on the diesel generators.
	EEX	EEX	the recoverable gas turbine exhaust.
	EEXD	EEXD	the recoverable diesel exhaust heat.
	EEXDT	EEXDT	the energy of the diesel exhaust gas.
	EFF	EFF	the efficiency of the engine generator.
	EFUEL	EFUEL	the fuel consumed by the gas turbine generators.
	EFUELD	EFUELD	the fuel consumed by the diesel generators.
	EJACKD	EJACKD	the recoverable jacket heat.
	EJL	EJL	the sum of the recoverable jacket and lube oil heat.
	ELUBED	ELUBED	the recoverable lube oil heat.
DIESEL-I/O-FPLR	RELD	f_1	a quadratic expression for the efficiency of the diesel as a function of the part load ratio.
GTURB-I/O-FPLR	FUEL1G	f_{1g}	a quadratic expression for the gas turbine fuel consumption as a function of part load ratio.
DIESEL-JAC-FPLR	RJACD	f_2	a quadratic expression for the recoverable jacket heat as a function of part load ratio.
GTURB-I/O-FT	FUEL2G	f_{2g}	a quadratic expression for the gas turbine fuel consumption as a function of air temperature.
DIESEL-LUB-FPLR	RLUBD	f_3	a quadratic expression for the recoverable lube oil heat as a function of part load ratio.

Keywords	FORTRAN Variables	Engineering Variables	Description
DIESEL-EXH-FPLR	REXD	f_4	a quadratic expression for the energy of the exhaust gas as a function of the part load ratio.
DIESEL-TEX-FPLR	TEXD	f_5	a quadratic expression for the exhaust gas temperature as a function of part load ratio.
GTURB-EXH-FT	FEXG	f_6	a quadratic expression for the gas turbine exhaust gas flow rate as a function of ambient air temperature.
GTURB-TEX-FPLR	TEX1G	f_7	a quadratic expression for the gas turbine exhaust gas temperature as a function of part load ratio.
GTURB-TEX-FT	TEX2G	f_8	a quadratic expression for the gas turbine exhaust gas temperature as a function of ambient air temperature.
	FEX	FEX	the gas turbine exhaust flow rate.
	FEXD	FEXD	the diesel exhaust gas flow. (lbs/hr)
	RLOAD	RLOAD	part load ratio.
MIN-RATIO	RMIN	RMIN	minimum part load ratio.
MAX-DIESEL-EXH	RMXKWD	RMXKWD	maximum exhaust gas flow rate per kilo watt.
MAX-GTURB-EXH	RMXKWG	RMXKWG	
		TAIR	the ambient air temperature.
	TEX	TEX	the diesel exhaust gas temperature.
	TSATUR	TSATUR	the steam saturation temperature.
	TSTACK	TSTACK	the exhaust stack temperature (after the heat exchange).
DIESEL-STACK-FU	UACD(1) UACD(2)	UACD(1) UACD(2)	the two terms of an expression for the calculation of the UA of the diesel (D) or gas (G) generator.
GTURB-STACK-FU	UACG(1) UACG(2)	UACG(1) UACG(2)	

Keywords	FORTRAN Variables	Engineering Variables	Description
	UAD	UAD	the hourly heat exchanger UA factor for the diesel generator.
	UAG	UAG	the hourly heat exchanger UA factor for the gas turbine generator.

2.2.7.1 Diesel Engine Generator (subroutine DIESEL)

Subroutine DIESEL simulates a diesel engine-generator set. This algorithm uses an efficiency curve to calculate fuel consumption (see Sec. V.2.2.1 for explanation of adjustment curves and associated limitations). In addition, attempted operation below the minimum part load ratio will cause the diesel to not operate, as contrasted to the cycling behavior of boilers and chillers below the minimum part-load ratio.

The part load ratio is

$$RLOAD = EELECD/CAP \tag{V.40}$$

where EELECD is the load on the diesels and CAP is the design (rated) capacity of the diesels operating this hour. If RLOAD is less than the minimum part load ratio RMIN (keyword MIN-RATIO), the diesel will not operate.

The efficiency of the engine-generator is

$$EFF = f_1(RLOAD) \tag{V.41}$$

where $f_1()$ is a quadratic function whose terms are stored in the array RELD and can be input through the keyword DIESEL-I/O-FPLR. The fuel consumed is

$$EFUELD = EELECD/EFF. \tag{V.42}$$

If the user specifies DIESEL-JACKET as a supply in the HEAT-RECOVERY command, the recoverable heat from both the diesel jacket fluid and the lubrication oil are calculated.

The recoverable jacket heat is calculated in terms of the fuel input and the part-load ratio

$$EJACKD = EFUELD * f_2(RLOAD). \tag{V.43}$$

$f_2()$ is a quadratic equation whose terms are stored in RJACD and can be input through the keyword DIESEL-JAC-FPLR.

The recoverable lube oil heat is also calculated in terms of the fuel input and the part load ratio

$$ELUBED = EFUELD * f_3(RLOAD). \tag{V.44}$$

$f_3()$ is a quadratic equation whose terms are stored in RLUBD and can be input through the keyword DIESEL-LUB-FPLR.

The sum of the recoverable jacket and lube oil heat is

$$EJL = EJACKD + ELUBED. \tag{V.45}$$

EJL is stored in the heat recovery supply array HTAVAL, for use in the heat recovery algorithm.

The user may specify heat recovery from the diesel exhaust by code-word DIESEL-GEN. The recoverable exhaust heat is calculated as a function of the exhaust gas temperature and flow rate, the steam saturation temperature, and the heat exchanger UA factor.

The energy of the exhaust gas (Btu/hr relative to 32°F) is

$$EEXDT = EFUELD * f_4(RLOAD). \tag{V.46}$$

$f_4()$ is a quadratic equation whose terms are stored in REXD and can be input through the keyword DIESEL-EXH-FPLR.

The exhaust gas temperature is

$$TEX = f_5(RLOAD) \tag{V.47}$$

where $f_5()$ is a quadratic equation whose terms are stored in TEXD and can be input through the keyword DIESEL-TEX-FPLR.

The exhaust gas flow (in lbs/hr) is calculated from the exhaust energy and temperature

$$FEXD = \frac{EEXDT}{\left(.25 \frac{Btu}{°F}\right) * (TEX - 32°F)} \tag{V.48a}$$

or

$$FEXD = \frac{CAP}{\left(3413\ \frac{Btu}{°F}\right) * (RMXKWD)}, \tag{V.48b}$$

whichever is smaller.

Where RMXKWD is the maximum exhaust gas flow rate/kw and corresponds to the keyword MAX-DIESEL-EXH.

The heat exchanger UA factor is assumed to vary with the hourly operating capacity

$$UAD = UACD(1)[CAP^{UACD(2)}]. \tag{V.49}$$

The terms of UACD correspond to the first two terms of the keyword DIESEL-STACK-FU.

The exhaust stack temperature (after the heat exchange) is

$$TSTACK = TSATUR + \left\{(TEX-TSATUR) * \left[e^{\left(\frac{-4UAD}{FEXD}\right)}\right]\right\} \tag{V.50}$$

where TSATUR is the steam saturation temperature (calculated in subroutine DEFALT, Sec. V.2.2.1) and the exponential term is the heat exchange effectiveness. This expression assumes the exhaust heat is recovered by generating steam in a stack jacket heat exchanger through which water at the saturation temperature of boiler steam is flowing.

The recoverable exhaust heat is

$$EEXD = (FEXD) * (.25\ Btu/lb°F) * (TEX-TSTACK). \tag{V.51}$$

Like EJL, EEXD is stored in the heat recovery supply array HTAVAL for use in the heat recovery algorithm.

2.2.7.2 Gas Turbine Generator (subroutine GASTUR)

Subroutine GASTUR simulates a gas turbine generator set.

The part-load ratio is

$$RLOAD = \frac{EELEC}{CAP}, \tag{V.52}$$

where EELEC is the electrical load on the gas turbines and CAP is the design (rated) capacity of the gas turbines operating this hour. If RLOAD is less than the minimum part-load ratio, RMIN (keyword MIN-RATIO), the gas turbines will not operate.

The fuel consumed is

$$EFUEL = EELEC * f_{1g}(RLOAD) * f_{2g}(TAIR), \tag{V.53}$$

where f_{1g} is a quadratic equation whose terms are stored in the array FUEL1G and can be input through the keyword GTURB-I/O-FPLR. It corresponds to the inverse of the efficiency at part load. TAIR is the ambient air temperature. f_{2g} is a quadratic equation whose terms are stored in FUEL2G and can be input through the keyword GTURB-I/O-FT.

The user may specify heat recovery from the turbine exhaust gas through the code-word GTURB-GEN. The recoverable exhaust gas heat is calculated as a function of the exhaust gas temperature and flow rate, the steam saturation temperature, and the heat exchanger UA factor.

The exhaust gas flow rate is

$$FEX = CAP * f_6(TAIR) \tag{V.54a}$$

or

$$FEX = \frac{CAP}{3413 \text{ Btu/kw}} * RMXKWG, \tag{V.54b}$$

whichever is smaller. $f_6()$ is a quadratic equation whose terms are stored in the array FEXG and can be input through the keyword GTURB-EXH-FT. This expression assumes that the flow rate is a function of the air temperature only. RMXKWG is the maximum exhaust gas flow rate/kw and corresponds to the keyword MAX-GTURB-EXH.

The exhaust gas temperature is

$$TEX = f_7(RLOAD) * f_8(TAIR), \tag{V.55}$$

where f_7 and f_8 are quadratic equations whose terms are stored in the array TEX1G and TEX2G respectively. They can be input through the keywords GTURB-TEX-FPLR and GTURB-TEX-FT.

The heat exchanger UA factor is assumed to vary with the hourly operating capacity

$$UAG = UACG(1) * CAP^{UACG(2)}. \tag{V.56}$$

The terms of UACG correspond to the first two terms of the keyword GTURB-STACK-FU.

The exhaust stack temperature (after the heat exchanger) is

$$TSTACK = TSATUR + \left\{ (TEX - TSATUR) * \left[e^{\left(-4 * \frac{UAG}{FEX}\right)} \right] \right\}, \tag{V.57}$$

where TSATUR is the steam saturation temperature and the exponential term is the heat exchange effectiveness. This expression assumes the exhaust heat is recovered by generating steam in a stack jacket heat exchanger through which water at the saturation temperature of boiler steam is flowing.

The recoverable exhaust heat is

$$EEX = FEX * .25\ Btu/lb^{\circ}F * (TEX - STACK). \tag{V.58}$$

EEX is stored in the heat recovery supply array $HTAVAL_i$ for use in the heat recovery algorithm.

2.2.8 Load Allocation Routines

The user of DOE-2 has the option of either defining how the heating, cooling, and electrical loads are to be distributed to the various equipment types, or he can allow the program to determine the operation of the equipment by default. There are advantages to both of the methods of operation. For example, if the user has only one type of boiler or chiller (and possibly multiple sizes of that equipment), it may be best to allow the program to default their operation. On the other hand, if the user wants to use a diesel generator solely for peak shaving of electrical loads, or he wants to use storage tanks, or he has both absorption and compression chillers in the same plant and he has specific ideas on how they should be operated, then he should specify their operation through the LOAD-MANAGEMENT and LOAD-ASSIGNMENT commands.

Variable List:

Keyword	FORTRAN Variables	Engineering Variables	Description
	ANUM	ANUM	The number of pieces of an equipment size needed to meet the load. This is a real number and can have a fractional value.

Keyword	FORTRAN Variables	Engineering Variables	Description
		CABS	The cooling load allocated to the absorption chillers, Btu.
		CAPA	The maximum load the absorption chillers can be given, Btu.
		CAPAM	The minimum load an absorption chiller can be given without cycling on and off, Btu.
		CAPC	The maximum cooling load that can be given to the compression chillers - both conventional and double bundle. (CAPC = CAPC1 + CAPC2, Btu)
		CAPC1	The maximum cooling load that can be given to conventional compression chillers, Btu.
		CAPC2	The maximum cooling load that can be given to double bundle compression chillers, Btu.
		CAPCM	The minimum cooling load that can be given to the smallest conventional or double bundle compression chiller without causing the chiller to false load, Btu.
		CAPC1M	The minimum cooling load that can be given to a conventional compression chiller without causing it to false load, Btu.
		CAPC2M	The minimum cooling load that can be given to a double bundle compression chiller without causing it to false load, Btu.
	CAPMAX	CAPMAX	The maximum possible capacity of a piece of equipment.
	CAPNEW	CAPNEW	The design capacity of a new piece of equipment turned on in the RUN-NEEDED mode.
	CAPOPQ	CAPOPQ	The total capacity of this equipment combination. It is the sum of the $CNOMQ_i$ in the combination.

Keyword	FORTRAN Variables	Engineering Variables	Description
	CCHEAP	CCHEAP	The amount of "cheap" cooling obtained.
		CCOMP	The cooling load allocated to the conventional compression chillers. During some intermediate steps, CCOMP can be the cooling load allocated to both types of compression chillers, conventional and double bundle, Btu.
		CDBUN	The cooling load on the double bundle chillers.
	CFREE	CFREE	The amount of "free" cooling obtained from waste generator heat.
		CLEFT	The cooling load left after calculation of solar, free, and cheap cooling.
	CNOM	$CNOM_{ji}$	The design capacity of the jth size of the ith type of equipment.
		$CNOMQ_i$	The available capacity of a single unit of a given size of equipment. (The design capacity adjusted for off-design conditions).
	CSOLAR	CSOLAR	The cooling obtained from solar energy.
	DEMND	DEMND	The cooling load to be allocated to the equipment.
	ECOOLT	ECOOLT	The cooling load to be allocated to the various chiller types, Btu.
		ELCOMP	The maximum amount of electricity that can be used by the compression chillers.
	EQDEM	$EQDEM_{1,i}$	The load allocated to each equipment type in the RUN-ALL mode of operation.
	EXCES1 EXCES2	$EXCES_i$	The amount of energy that could be shifted from an equipment type without causing cycling or false loading.
		GADD	The additional load to be placed on the electric generators to accomplish cheap cooling.
		GLEFT	The unused generator capacity.

Keyword	FORTRAN Variables	Engineering Variables	Description
		GLOAD	The generator electrical output.
	GUESS	GUESS	The "predicted" load calculated to determine the appropriate LOAD-ASSIGNMENT.
		HTABS	The amount of waste heat available for use in the absorption chiller.
	HTAVAL	$HTAVAL_i$	The energy available from a storage tank.
		HTDBUN	The heating load that might be satisfied by a double bundle chiller. It is initially set to the space heating load. If the double bundle chiller is hooked up to a hot storage tank in the HEAT-RECOVERY command, the storage demand is also included.
		HTEXH	The high temperature (~370°F) waste heat recoverable from the generator exhaust gases.
		HTGEN	The total recoverable waste heat from the generator.
		HTJAC	The lower temperature (~250°F) waste heat recoverable from the jacket of the diesel engine.
		HTNEED	The domestic/process heating load not satisfied by generator waste heat.
	HTREQD(25)	$HTREQD_{25}$	The space heating loads passed from SYSTEMS to PLANT.
	HTREQD(26)	$HTREQD_{26}$	The domestic/process heat load passed from SYSTEMS to PLANT.
MAX-NUMBER-AVAIL	KAV	KAV_i	The number of each size of the equipment type.
	KAVQ	$KAVQ_i$	Equal to KAV_i + 1.
	LOAD	LOAD	The cooling, heating or electrical load to be allocated.
	NCOMBS	NCOMBS	The number of possible combinations of equipment for a given type of load.

Keyword	FORTRAN Variables	Engineering Variables	Description
	NEQ	NEQ	The number of different sizes of a type of equipment.
	NUM	NUM	The number of this size of equipment operating during a RUN-NEEDED operation. This is ANUM rounded up.
NUMBER	NUMBER	NUMBER	The quantity of a given type of equipment that is input as a LOAD-ASSIGNMENT pair (that is, PLANT-EQUIPMENT = and NUMBER =).
	OPCAP	$OPCAP_i$	The hourly design operating capacity of each type of equipment.
	PDEM(2)	$PDEM_2$	The space cooling load passed from SYSTEMS to PLANT.
	PDEM(3)	$PDEM_3$	The electrical load passed from SYSTEMS to PLANT.
		RAC	The proportionality factor to determine which loads should be given to the absorption and compression chillers.
	RCAP	$RCAP_i$	The available capacity ratio. $RCAP_i$ = 1 except for chillers whose capacities vary with temperature.
	RELCOM	RELCOM	The ratio of the compression chiller electrical consumption to the compression chiller output. It is the weighted average of the ELEC-INPUT-RATIOs of the conventional and double bundle compression chillers, $Btu_{elec}/Btu_{cooling}$.
	REMAIN	REMAIN	The load still remaining to be allocated.
	REQD	REQD	The minimum load required on a chiller to prevent cycling or false loading.
		RHTABS	The ratio of the absorption chillers heat consumption to the absorption chiller output. It is the same as the ABSOR#-HIR, where # corresponds to the particular type of absorption chiller - 1, 2, or S, $Btu_{heat}/Btu_{cooling}$.

Keyword	FORTRAN Variables	Engineering Variables	Description
		RHTDB	The ratio of double bundle chiller rejected heat to the double bundle chiller load. This quantity is calculated in the design routine.
		RHTGEN	The ratio of the recoverable waste heat output of the diesel and gas turbine generators to their electrical output, Btu_{waste}/Btu_{elec}.
MAX-RATIO	RMAX	RMAX	The ratio of the maximum capacity allowed to the design capacity.
MIN-RATIO [*]-UNL-RATIO	RMIN1	$RMIN1_i$	The ratio of the minimum capacity for which the machine will continue to operate to the design capacity.
	SHIFT	SHIFT	The load that is transferred from one equipment type to another to prevent cycling or false loading.
		SOLHT	The solar heat available for cooling.
		SPACHT	The sum of the space, process, and domestic heating loads.
	SUM	SUM	The sum of the maximum capacities of all the equipment types being used to meet a given load.
	TNKMCP	TNKMCP	The heat capacity of the solar storage tank.
	TNKT	TNKT	The solar storage tank temperature.
MIN-SOL-COOL-T	TSOL	TSOL	The minimum temperature at which solar heat is usable for cooling.
		X	The waste heat available to decrease the double bundle chiller potential heating load.
COOL-MULTIPLIER	AA		The ratios of the managed loads (see Sec. V.2.2.8.2) to the total rated capacity of the equipment.
HEAT-MULTIPLIER	AA		
ELEC-MULTIPLIER	AA		

[*] may be replaced by OPEN-REC, OPEN-CENT, HERM-REC, HERM-CENT as appropriate.

2.2.8.1 User Defined Equipment Operation

2.2.8.1.1 LOAD-ASSIGNMENT (subroutine EQUIP)

EQUIP uses the data entered under the LOAD-ASSIGNMENT command to determine the sequence in which the plant equipment is to be assigned to serve the heating, cooling, or electrical load.

The load to be allocated, LOAD, is compared to the load range (keyword LOAD-RANGE) to determine the set of equipment and possibly a utility to be used to meet the load. The algorithm starts with the first (smallest) load range entered by the user. If LOAD is greater than the value of the load range, then the algorithm compares LOAD to the next load range and repeats the cycle until the value of the load range is greater than the LOAD. If the algorithm runs out of load ranges before finding one greater than the LOAD, then the last load range entered is used. The load ranges must be entered in increasing numerical order. The results will be meaningless otherwise. Once the correct load range has been found, the LOAD can be allocated to the equipment set listed under that load range.

The algorithm allocates the LOAD to the equipment differently, depending on whether the user chooses the RUN-ALL or RUN-NEEDED mode. When in the RUN-ALL mode, all pieces of equipment in the set are operated simultaneously to meet the LOAD. The LOAD is allocated to each equipment piece in proportion to that piece's capacity. In the RUN-NEEDED mode, the pieces of equipment in the list are turned on sequentially until the LOAD is satisfied. Hence, depending on the LOAD, equipment toward the end of the list may not be operated when in the RUN-NEEDED mode.

Storage tanks require additional calculations in this algorithm. The special case of storage tanks is discussed in more detail in Sec. V.2.2.4.

RUN-ALL Operation.

The hourly design operating capacity of each type of equipment listed is

$$OPCAP_i = \sum_{j}^{list} CNOM_{ji} * NUMBER, \qquad (V.59)$$

where $CNOM_{j,i}$ is the array in which all the design capacities of each type of equipment are stored. The subscripts j,i are set to reference the size and type of the equipment units listed in the PLANT-EQUIPMENT = U-name keyword pairs of the load range being used. If a storage tank is being called upor, $OPCAP_i$ for the tank is set to the energy available from the tank, $HTAVAL_i$.

The sum of the maximum capacities of all the equipment types being used to meet the LOAD is

$$SUM = \sum_i OPCAP_i * RCAP_i * RMAX_i. \qquad (V.60)$$

$RCAP_i$, the available capacity ratio, is always set to unity, except for chillers whose capacities vary with their operating temperatures. $RMAX_i$ is the ratio of the maximum capacity allowed to the design capacity and corresponds to the keyword MAX-RATIO.

The load is allocated to each equipment type (for all sizes of this type turned on) in proportion to its maximum capacity.

$$EQDEM_{1,i} = LOAD * \frac{OPCAP_i * RCAP_i * RMAX_i}{SUM} \qquad (V.61a)$$

or

$$EQDEM_{1,i} = OPCAP_i * RCAP_i * RMAX_i, \qquad (V.61b)$$

whichever is smaller.

The subscript i corresponds to the equipment type being allocated a load. Equation (V.61) is repeated for each equipment type listed under the LOAD-RANGE being used. If Eq. (V.61b) is chosen over Eq. (V.61a), part of the load will be unsatisified. The remaining load is

$$REMAIN = LOAD - \sum_i EQDEM_{1,i} \qquad (V.62)$$

where the subscript i refers to the equipment being used to meet the LOAD. If REMAIN is greater than zero, an overload condition exists. This overload will be met by the electrical, steam or chilled water utility if the user is allowing that utility to be used (see the ENERGY-COST command in the reference manual). Also, REMAIN can be reduced or eliminated if part of the LOAD is from a storage demand of a tank. Aside from these two exceptions, REMAIN will ultimately be reported as an overload in the summary reports.

<u>RUN-NEEDED Operation</u>.

Here, equipment is turned on sequentially in the order listed under the LOAD-RANGE being used. The remaining load is decreased as each piece of equipment is turned on.

The remaining load is initially set to the total load to be allocated

$$REMAIN = LOAD. \tag{V.63}$$

Equations (V.64) through (V.71) are repeated for each PLANT-EQUIPMENT = U-name keyword pair entered under the LOAD-RANGE being used.

The design size of the piece being turned on is

$$CAPNEW = CNOM_{ji}. \tag{V.64}$$

For the direct cooling THERMO-CYCLE mode (using chillers as heat exchangers),

$$CAPNEW = CAPNEW * RCAP_i.$$

CAPNEW = 0 for chillers that are not compatible with this cooling mode.

$CNOM_{ji}$ is the array in which all the sizes of each type of PLANT-EQUIPMENT are stored. The subscripts j,i are set to reference the size and type of the equipment referred to by the PLANT-EQUIPMENT = U-name keyword pair being processed.

The maximum capacity of the piece being turned on is

$$CAPMAX = CAPNEW * RCAP_i * RMAX_i. \tag{V.65}$$

The number of pieces of this equipment size needed is

$$ANUM = \frac{REMAIN}{CAPMAX} \text{ or NUMBER, whichever is smaller.} \tag{V.66}$$

ANUM is a real number and can have a fractional value, as can NUMBER. The actual number of this equipment size operating must be an integer

$$NUM = ANUM \text{ rounded up.} \tag{V.67}$$

The hourly nominal operating capacity of all sizes of this equipment type is increased by the integer number of pieces just turned on

$$OPCAP_i = OPCAP_i + (CAPNEW * NUM). \tag{V.68}$$

The load that has just been allocated to the equipment can be less than or equal to the maximum capacity

$$DEMND = CAPMAX * ANUM. \tag{V.69}$$

The total demand on all sizes of this equipment type is increased

$$EQDEM_{1,i} = EQDEM_{1,i} + DEMND \tag{V.70}$$

and the remaining load to be allocated is decreased

$$REMAIN = REMAIN - DEMND. \tag{V.71}$$

Equations (V.64) through (V.71) are repeated for each PLANT-EQUIPMENT = U-name keyword pair until REMAIN is zero or there are no keyword pairs left. When finished, the program checks to see if REMAIN is zero. If it isn't, then an overload condition identical to that discussed in the RUN-ALL section exists.

Because the equipment is turned on sequentially in the RUN-NEEDED mode, it is possible that the last equipment type turned on may be given an extremely small load while another equipment type may be operating at maximum capacity. The algorithm checks to see if the last type turned on is operating at a part load ratio so small that it is cycling on and off during the hour (keyword MIN-RATIO) or, in the case of compression chillers, false loading (keywords OPEN-CENT-UNL-RATIO etc.). If it is, the algorithm will attempt to shift part of the load from the equipment operating at maximum capacity to the equipment cycling or false loading. Of course, if there is only one equipment type operating, there is nothing the algorithm can do.

The amount of energy to be shifted to the equipment type with the low load is the difference between the amount it needs to avoid cycling or false loading, and the amount it has already been given

$$REQD = (OPCAP_i * RCAP_i * RMIN1_i) - EQDEM_{1,i}. \tag{V.72}$$

RMIN1 corresponds to the keywords MIN-RATIO or OPEN-CENT-UNL-RATIO, etc., as appropriate for this type equipment.

The algorithm attempts to shift the REQD amount of energy from the other equipment types operating. When shifting the load, the algorithm prevents any cycling or false loading of the equipment the load is being shifted from. The amount of energy that can be shifted from an equipment type is

$$EXCES_i = EQDEM_{1,i} - (OPCAP_i * RCAP_i * RMIN1_i). \tag{V.73}$$

The algorithm allows the load to be shifted to one equipment type from up to two other equipment types. The equipment types losing their loads will lose them in proportion to their capacities. The sum of the loads that can be shifted is

$$SUM = \sum EXCES_i . \tag{V.74}$$

The amount actually shifted is

$$SHIFT = REQD \text{ or } SUM, \text{ whichever is smaller.} \tag{V.75}$$

The loads are now readjusted. The load on the equipment type that needed extra loading is

$$EQDEM_{1,i} = EQDEM_{1,i} + SHIFT \tag{V.76}$$

and the loads on the equipment types that were unloaded are

$$EQDEM_{1,i} = EQDEM_{1,i} - \left(SHIFT * \frac{EXCES_i}{SUM} \right) . \tag{V.77}$$

2.2.8.1.2 LOAD-MANAGEMENT (subroutine EQPTRS)

Subroutine EQPTRS uses the data entered under the LOAD-MANAGEMENT command to decide which LOAD-ASSIGNMENTS, if any, are to be used to allocate the loads to the equipment.

The "predicted load" that will be used to choose the appropriate LOAD-ASSIGNMENTs is

$$GUESS = (HTREQD_{25} * \text{HEAT-MULTIPLIER}) + (PDEM_2 * \text{COOL-MULTIPLIER})$$
$$+ (PDEM_3 * \text{ELEC-MULTIPLIER}), \tag{V.78}$$

where $HTREQD_{25}$, $PDEM_2$, and $PDEM_3$ are the space heating, space cooling, and electrical loads passed from SYSTEMS to PLANT. These loads are exclusive of any additional loads generated by the plant equipment. HEAT-MULTIPLIER, COOL-MULTIPLIER, and ELEC-MULTIPLIER are the ratios of the managed heating, cooling, and electrical loads to the total rated capacity of the equipment.

GUESS is compared to the predicted load range (PRED-LOAD-RANGE) to determine the set of equipment to be operated (LOAD-ASSIGNMENTs) or the user-assigned schedules (ASSIGN-SCHEDULEs) to be followed. The algorithm starts with the first (smallest) predicted load range entered by the user. If GUESS is greater than the value of the predicted load range, then the algorithm compares GUESS to the next load range and repeats the cycle until the value of the predicted load range is greater than the value of GUESS. If the algorithm runs out of predicted load ranges before finding one that is greater than GUESS, then the last predicted load range entered is used (i.e., the algorithm assumes that the values of the predicted load ranges are entered in increasing numerical order). The results may be meaningless otherwise. Once the correct PRED-LOAD-RANGE is found, pointers to the heating, cooling, and electrical LOAD-ASSIGNMENTs to be used this hour are stored in the array LATYPE. If a LOAD-ASSIGNMENT has not been specified for a certain type of load (heating, cooling, and/or electrical), a 0 is stored in the LATYPE array to indicate to the program that the equipment allocation to this type of load should be defaulted.

2.2.8.2 Default Equipment Operation

The default equipment allocation is carried out in two parts. Part 1 determines the optimum distribution of the cooling and electrical loads between various types of equipment. Part 2 then distributes the cooling, heating, and electrical loads among equipment of a single type.

2.2.8.2.1 Optimum Distribution of Cooling Load to Multigeneric Types (routines OPCOOL and OPCOLD)

Introduction

The routine OPCOOL allocates the cooling load to absorption chillers and single and double bundle compression chillers. It is the default allocation alogrithm; it is used when the user has chosen not to input one or more LOAD-ASSIGNMENT commands to control the chillers. OPCOOL is capable of allocating the load to, at most, one type of absorption chiller, one type of single bundle compression chiller, and double bundle chillers. Multiple units and sizes of these chillers are allowed. Section V.B.1 of the DOE-2 Reference Manual (Ref. 2) discusses the precedence rules governing the use of more than one absorption chiller type or more than one compression chiller type.

The manner in which OPCOOL allocates the load varies, depending upon which of the following cases applies:

1. There is only one type of chiller. In this case, the entire cooling load will be allocated to this chiller type, up to the maximum total chiller capacity available.

2. There are double bundle compression chillers together with another type of chiller. In this case, the double bundle chiller will only be given enough load so that it can satisfy the space heating load with its waste heat. The rest of the cooling load will be allocated as in case 3.

3. There are both absorption and compression chillers present, but no electrical generators or solar equipment capable of supplying heat to the absorption chillers. In this case, the load is preferentially allocated to the chiller type that uses the least amount of source energy.

4. There are both absorption and compression chillers present with either electrical generators capable of supplying waste heat and/or solar equipment. In this case, enough of the cooling load is allocated to the absorption chillers so that they can make use of this "free" energy. The rest of the cooling load is allocated as in case 3. It is assumed that space heat and process heat take priority on waste heat before absorption chillers.

In cases 3 and 4, any double bundle chillers present are assumed to be a subset of single bundle chillers. Double bundle chillers will be given part of the compression chiller load only if their capacity is needed to meet the cooling load. Note, if there is a space heating load, case 2 applies.

OPCOOL attempts to allocate the cooling load in such a manner that no equipment type is being operated extremely inefficiently (absorption chillers cycling on and off or compression chillers false loading). Additionally, no equipment type is given a load greater than its maximum operating capacity.

This algorithm has been written to handle a wide range of plant configurations. However, if solar is a supply to both process heat and to an absorption chiller, and there are also compression chillers and electric generators in the same plant, the absorption chiller may not be allocated as much of the cooling load as it should. Fortunately, this configuration is not very likely.

With the partial exception of the electrical generators, it is assumed that the input/output relationships of the equipment can be approximated by their full-load energy input ratios (ELEC-INPUT-RATIO or ABSOR1-HIR for example). The generator input/output ratios are calculated hourly based on the electrical load coming from SYSTEMS and the anticipated tower load.

OPCOOL allocates the cooling load to the various chiller types. LDIST is then called to decide how many of which size of each chiller type will be used to meet the load allocated to that type.

Routine OPCOLD

This routine precalculates some variables at the beginning of the simulation and stores them for later use in subroutine OPCOOL, the cooling optimization routine.

1. For absorption chillers, the ratio of heat input to cooling output is:

$$RHTABS = HIRNOM_i$$

where $HIRNOM_i$ corresponds to the heat input ratio specified through the keywords ABSOR1-HIR and ABSOR2-HIR, depending on the type of absorption chiller.

2. For compression chillers, the ratio of electrical input to cooling output is

$$RELCOM = \frac{\left(EIR_{ICOMPR} * TOTCAP_{ICOMPR}\right) + \left(EIR_{double\text{-}bundle} * TOTCAP_{double\text{-}bundle}\right)}{TOTCAP_{ICOMPR} + TOTCAP_{double\text{-}bundle}} .$$

RELCOM is the weighted average of the single bundle and double bundle chiller if both exist, EIR_i is the respective electrical input ratio, and $TOTCAP_i$ is the respective total capacity.

3. The total electrical generating capacity (excluding steam turbines) is:

$$TCAPDG = TOTCAP_{diesels} + TOTCAP_{gas\text{-}turbines} .$$

4. When generators are present, OPCOOL will need to know an estimate of the tower electrical consumption when the absorption chillers are running. The heat rejection from the absorption chillers at design conditions is calculated and the tower is simulated. The electricity consumed by the tower is stored in TWRELC for hourly use in subroutine OPCOOL.

5. When there are no constraints on how cooling can be allocated between absorption and compression chillers, OPCOOL will preferentially load the type of chiller that consumes the least amount of source energy per Btu of cooling produced.

   The source energy per Btu of cooling for absorption chillers is:

$$X = HIR_{abs} * HIR_{boiler}$$

   where HIR_{abs} is the heat input ratio of the absorption chiller in $Btu_{heat}/Btu_{cooling}$ and HIR_{boiler} is the heat input ratio of the fossil-fuel boiler in $Btu_{boiler\ fuel}/Btu_{heat}$.

   The source energy per Btu of cooling for compression chillers is:

$$Y = EIR_{comp}/UDATA$$

where EIR_{comp} is the electric input ratio of the compression chiller in $Btu_{elec}/Btu_{cooling}$ and UDATA is an array containing the value for the source-to-site conversion efficiency in Btu_{site}/Btu_{source}, input through the keyword SOURCE-SITE-EFF in the ENERGY-COST command.

6. For double bundle chillers, the ratio of rejected heat to load is

$$RHTDB = (1.0 + EIR) * RKWREC$$

where RKWREC is the fraction of rejected heat that is recoverable, input through the keyword DBUN-HT-REC-RAT. RHTDB is used to decide how much of the cooling load is to be given to the double bundle chillers.

7. Finally, OPCOOL must know the minimum size for the chillers. The minimum size is stored in CMINA, CMINC, and CMINDB for absorption, compression, and double bundle chillers, respectively.

Routine OPCOOL

The cooling optimization calculations are done in the following sequence:

Step 1. Calculate solar cooling, if any.
Step 2. Calculate waste heat from generators, if any,
Step 3. Using results of 1 and 2, calculate the "free cooling".
Step 4. Calculate cheap cooling.
Step 5. Calculate coupled cooling.
Step 6. General allocation.
Step 7. Adjust loads for underloaded equipment.

Step 1. Solar Cooling.

If the user has hooked up solar energy to an absorption chiller, this section determines how much of the cooling load should be given to the absorption chillers.

The solar heat available for cooling is

$$SOLHT = [(TNKT - TSOL_3) * TNKMCP] - HTREQD_{26}$$

where TNKT is the solar tank temperature, $TSOL_3$, is the minimum temperature at which the solar heat is usable for cooling (keyword MIN-SOL-COOL-T), and TNKMCP is the heat capacity of the tank. $HTREQD_{26}$ is the domestic/process heat load and is assumed to have priority on solar heat.

The cooling that can be accomplished using solar energy is

$$CSOLAR = \frac{SOLHT}{RHTABS} \qquad (V.79)$$

or ECOOLT or CAPA, whichever is smaller. RHTABS is the heat-input ratio of the chiller, ECOOLT is the cooling load to be allocated, and CAPA is the maximum load the chiller can handle. CSOLAR will be included in the absorption chiller load, CABS, in Step 5.

Step 2. Generators.

To determine the waste heat available from the generators for use in satisfying space heating, process water heating, and absorption cooling heat loads, the generators are simulated. The total electrical load at this point is not yet known as no type of plant equipment other than pumps and solar equipment has been simulated. The generators are simulated in OPCOOL based on the electrical load needed through the SYSTEMS program and the expected tower load (TWRELC, predicted in OPCOLD). The assumption here is that the absorption chillers will probably receive most of the cooling load (hence the compression chillers will not be using much additional electricity), the cooling tower will have all cells on high fan speed (the usual condition), and there is no improbable equipment in a plant with electric generators such as an electric boiler. The program will use either the default electrical load allocation routine or, if the user has input a LOAD-ASSIGNMENT for the generators, it will use the LOAD-ASSIGNMENT. This allows OPCOOL to know whether the generators are just being used for peak shaving or for base loading. With these ideas in mind, the following quantities are calculated:

GLEFT — The as yet unused generator capacity. It is the total generator capacity minus the part already used for the systems and tower electrical loads.

HTEXH — The high temperature (~370°F) waste heat recoverable from the generator exhaust gases. If the user did not hook up the exhaust to any demand in the HEAT-RECOVERY command, this quantity is always zero.

HTJAC — The lower temperature (~250°F) waste heat recoverable from the jacket of the diesel engine. If the user did not hook up the DIESEL-JACKET to any demand in the HEAT-RECOVERY command, this quantity is always zero.

HTGEN — The sum of HTEXH and HTJAC.

RHTGEN — The ratio of the recoverable generator waste heat to the generator electrical output, GLOAD

$$RHTGEN = \frac{HTGEN}{GLOAD}. \tag{V.80}$$

The quantities defined above are used in the free, cheap, and coupled cooling allocation strategies developed below. The calculation for RHTGEN assumes that deviations from the assumed electrical load are small enough so that the waste heat output can be approximated by a linear function.

Step 3. Free Cooling.

If the generators produce more waste heat than is needed by the space heating and domestic/process water heating loads, the excess waste heat is used in the absorption chillers to produce "free cooling".

If the chiller is a one-stage chiller, the amount of heat available for use in the absorption chiller is

$$HTABS = \begin{cases} (HTGEN - SPACHT) \text{ for } HTABS > 0 \\ 0 \text{ for } HTABS \le 0 \end{cases} \tag{V.81}$$

where SPACHT is the sum of the space and process heating loads. If the chiller is a two-stage machine, only the excess high temperature exhaust heat can be used. The SPACHT is first decremented by the available jacket heat

$$SPACHT = \begin{cases} (SPACHT - HTJAC) \text{ for } SPACHT > 0 \\ 0 \text{ for } SPACHT \le 0 \end{cases} \tag{V.82}$$

and

$$HTABS = \begin{cases} (HTEXH - SPACHT) \text{ for } HTABS > 0 \\ 0 \text{ for } HTABS \le 0. \end{cases} \tag{V.83}$$

The free cooling is now calculated in a manner analogous to solar cooling

$$CFREE = \frac{HTABS}{RHTABS} \tag{V.84}$$

or ECOOLT or CAPA, whichever is smaller. CFREE will be included in the absorption chiller load, CABS, later.

Step 4. Cheap Cooling.

If the generators did not produce enough waste heat to satisfy the space and domestic/process heating loads (thereby precluding "free cooling"), enough of the cooling load should be allocated to the compression chillers so that the increased electrical load will be large enough to produce the extra waste heat needed.

The additional heat needed is

$$HTNEED = SPACHT - HTGEN. \tag{V.85}$$

The maximum amount of electricity the compression chillers can use is

$$ELCOMP = ECOOLT * RELCOM \quad \text{or} \quad CAPC * RELCOM, \tag{V.86}$$

whichever is smaller. RELCOM is the average electric input ratio for the compression chillers and CAPC is the maximum cooling load that can be given to the compression chillers.

The additional load to be placed on the generators is

$$GADD = ELCOMP, \quad GLEFT, \text{ or } \quad \frac{HTNEED}{RHTGEN}, \tag{V.87}$$

whichever is smallest. The third quantity is the electrical load needed to produce the additional waste heat needed.

The cheap cooling is then

$$CCHEAP = \frac{GADD}{RELCOM}. \tag{V.88}$$

The remaining unused generator capacity is

$$GLEFT = GLEFT - GADD. \tag{V.89}$$

The remaining heating load the double bundle chiller might be able to satisfy (see the definition of HTDBUN) is

$$X = \begin{cases} [HTGEN + (GADD * RHTGEN) - HTREQD_{26}] \text{ for } X > 0 \\ 0 \text{ for } X \leq 0, \end{cases}$$

$$HTDBUN = \begin{cases} (HTDBUN - X) \text{ for } HTDBUN > 0 \\ 0 \text{ for } HTDBUN \leq 0, \end{cases} \tag{V.90}$$

where X is the waste heat available to decrease the double bundle chiller potential heating load. The first two terms in X are the total waste heat now being generated, and $HTREQD_{26}$ is the domestic/process heating load. The assumption is that since the double bundle chiller can satisfy space heat loads, but not domestic/process loads, domestic/process loads should be given priority on the generator heat. The double-bundle chiller may be called upon to supply this heat later in the algorithm.

<u>Step 5. Coupled Cooling.</u>

Once free cooling or cheap cooling has been accomplished, part of the cooling load may still be unallocated. If both absorption and compression chillers can accept additional cooling loads, and excess generator capacity remains, it is possible to couple the absorption and compression chillers to the generator so that the waste heat produced in generating electricity for the compression chillers is just enough to supply the absorption chillers. To couple the chillers so that no generator heat is wasted, and no extra boiler heat is needed, the following relationships are used:

a. The electricity required to produce cooling with compression chillers is

$$ELCOMP = CCOMP * RELCOM, \qquad (V.91)$$

where CCOMP is the cooling load to be allocated to the compression chillers in this step and RELCOM is the compression chiller electric input ratios.

b. The heat needed to produce cooling with absorption chillers is

$$HTABS = CABS * RHTABS, \qquad (V.92)$$

where CABS is the cooling load to be allocated to the absorption chiller in this step.

c. When coupled, the heat produced in generating the compression chiller electricity should be just enough for the absorption chiller

$$ELCOMP * RHTGEN = HTABS. \qquad (V.93)$$

RHTGEN was defined in Eq. (V.80) as the ratio of the total recoverable waste heat to the generator output. If a two-stage absorption chiller is being used, only the high temperature exhaust heat is usable and RHTGEN must be redefined as

$$RHTGEN = \frac{HTEXH}{GLOAD}.$$

d. Substituting Eqs. (V.91) and (V.92) into Eq. (V.93)

$$CCOMP * RELCOM * RHTGEN = CABS * RHTABS$$

or

$$CABS = CCOMP * RAC \tag{V.94}$$

where

$$RAC = \frac{RELCOM * RHTGEN}{RHTABS}. \tag{V.95}$$

RAC is the proportionality factor that determines how the load is split between the absorption and compression machines.

e. The as yet unallocated cooling load is

$$CLEFT = ECOOLT - CSOLAR - CFREE - CCHEAP. \tag{V.96}$$

This load will be allocated to the coupled absorption and compression chillers

$$CLEFT = CCOMP + CABS \tag{V.97a}$$

$$= CCOMP + (CCOMP * RAC). \tag{V.97b}$$

f. The coupled compression chiller load is either

$$CCOMP = \frac{CLEFT}{1 + RAC} \tag{V.98a}$$

or the remaining compression chiller capacity

$$CCOMP = CAPC - CCHEAP \tag{V.98b}$$

or the compression chiller capacity that can be powered by the remaining generator capacity

$$CCOMP = \frac{GLEFT}{RELCOM}, \tag{V.98c}$$

whichever is smaller.

g. The coupled absorption chiller load is either

$$CABS = CCOMP * RAC \tag{V.99a}$$

or the remaining absorption chiller capacity

$$CABS = CAPA - CSOLAR - CFREE, \tag{V.99b}$$

whichever is smaller.

Step 6. General Allocation.

The remaining unallocated cooling load is allocated in the following manner:

a. The absorption and compression chiller loads so far are

$$CABS = CABS + CSOLAR + CFREE \tag{V.100}$$

$$CCOMP = CCOMP + CCHEAP. \tag{V.101}$$

b. At this point, CCOMP is the compression chiller load, either conventional, double bundle, or both. The next step is to decide how much should be given to the double bundle chiller. If a double bundle chiller exists, and there is a use for its rejected heat, the double bundle cooling load is either

$$CDBUN = \frac{HTDBUN}{RHTDB} \tag{V.102a}$$

or

$$CDBUN = ECOOLT - CSOLAR \tag{V.102b}$$

or

$$CDBUN = CAPC2, \tag{V.102c}$$

whichever is less. RHTDB is the ratio of the double bundle heat output to the double bundle cooling output. RHTDB was precalculated in the design subroutine.

CAPC2 is the design capacity of the double bundle chillers. Only CSOLAR is deducted from the total cooling load in Eq. (V.102b). Because of the order in which the cooling load is allocated, HTDBUN would be zero if CFREE or CABS were nonzero, hence, the double bundle would not be needed.

If CCOMP is smaller than CDBUN, CCOMP is reset to CDBUN.

The remainder of the cooling load is now allocated between the absorption and compression machines. The allocation gives as much of the remaining cooling load to the type, up to its maximum capacity, that makes the most efficient use of source energy (compression chillers through an electric power plant, or absorption chillers through a boiler), with any remainder going to the other type.

The double bundle load is now separated from the conventional compression chiller load. The program makes a check to insure that, if the double bundle has been given a load, the load is large enough to prevent the double bundle from false loading. No other load is given to the double bundle unless its capacity is needed to meet the cooling load. The conventional compression chiller is

$$CCOMP = CCOMP - CDBUN.$$

CCOMP at this point is now only the conventional compression chiller load.

Step 7. Underloaded Equipment.

With the exception of the double bundle chiller, the program has not checked to see if compression chillers are false loading or absorption chillers are cycling on and off.

The program checks the conventional compression chiller load first. If CCOMP is less than the minimum load, CAP1M, the program tries to give CCOMP to the double bundle chillers, provided the double bundle chillers are turned on. If the double bundle chillers do not have enough remaining capacity to handle all of CCOMP, the program tries to shift part of the absorption chiller load to CCOMP, provided the absorption chillers are turned on. If the amount needed to be shifted to prevent the compression chillers from false loading is enough to cause the absorption chillers to cycle, then the program tries to give all of CCOMP to the absorption chillers. If this doesn't work, then conventional compression chillers will have to false load.

The above is repeated for when the absorption chillers are cycling, except that no attempt is made to give the absorption chiller load to the double bundle chillers.

OPCOOL has apportioned the total cooling load to each type of chiller. The routine LDIST is now called to allocate the load given to each type to the particular sizes and number of each size of each chiller type.

2.2.8.2.2 Optimum Distribution of Electrical Load (routines OPELEC and OPFUEL)

Routine OPELEC

The routine OPELEC allocates electric load between steam turbine- and fuel-consuming-electric generators (gas turbines and diesel engines). It calls the routine OPFUEL, which then allocates the latter electrical load between the two kinds of fuel-consuming generators.

OPELEC is called both from the main routine, PLANT, and from subroutine OPCOOL, but for two different purposes. OPELEC is called by PLANT for the purpose of making the load allocation for the final simulation. OPELEC is called by routine OPCOOL for the purpose of making a tentative allocation to determine the amount of waste steam that may be available to run absorption chillers. Some variables in routine OPELEC will thus have different values in these two different circumstances. As an example, the amount of electric load to be allocated in the first case (that is, with PLANT) is the actual load. In the second case (that is, with OPCOOL), the electric load is an estimate of the maximum likely electric load that will be used to make decisions on possible cooling load allocation.

Routine OPELEC contains the following assumptions:

1. If any electric generating equipment exists, as much as possible of the load is to be met by this equipment, and as little as possible is to be met by utility usage.

2. If there are both steam turbines and fuel-consuming generators, the most efficient load allocation is as follows. The amount of steam required by the steam turbine should be approximately equal to the exhaust steam from the fuel-consuming generators after subtracting any steam that could be used to run absorption chillers.

The algorithm employed is as follows:

Step 1. Set the result variables to zero.

Step 2. If the electric load is zero, or if no electric generators exist in the simulation, return to the cooling routine.

Step 3. If no steam turbines exist, skip to Step 35.

Step 4. Calculate the minimum portion of the electric load that a steam turbine must satisfy if it is to operate at its minimum operating ratio.

Step 5. If the electric load is less than the minimum operating ratio of the smallest steam turbine, skip to Step 35.

Step 6. Calculate the total maximum capacity of the fuel-consuming generators.

Step 7. Set the available waste steam quantity equal to the sum of the total heating load plus the estimated absorption chiller steam usage. This is a negative value.

Step 8. Determine the maximum portion of the electric load that steam turbines could meet.

Step 9. Estimate the steam turbine average ratio of input to output, by simulating one unit of the largest size steam turbine.

Step 10. Set the maximum portion of the electric load that the fuel-consuming generators could meet (and their waste heat outputs) to zero.

Step 11. If no fuel-consuming electric generators exist, skip to Step 30.

Step 12. Determine the maximum amount of fuel-consuming generator-exhaust steam potentially available, by allocating the entire electric load, if possible, to fuel-consuming generators. Then simulate the fuel-consuming generators allowing for any heating load and absorption chiller loads.

Step 13. If there is no excess exhaust steam available, skip to Step 30.

Step 14. Estimate the electric load that could be allocated to the steam turbine, assuming the turbine uses all of the excess exhaust steam calculated in Step 12. Assume initially that the steam turbine will be allocated this electric load and reduce the entire electric load by that amount. The remaining load will be met by the fuel-consuming generators.

Step 15. The reduced load on the fuel-consuming generators will also reduce the excess exhaust steam. Therefore, re-estimate the excess exhaust steam by assuming that the fuel-consuming generators will meet only the portion of the electric load now remaining (that is, following Step 14). The waste heat outputs for each of the fuel-consuming generators are reduced proportionally to maintain an energy balance.

Step 16. If the load is so high that all steam turbines must be used to meet it, skip to Step 30.

Step 17. Recalculate the steam turbine electric load as in Step 14, but using the reduced excess exhaust steam rate of Step 15.

Step 18. If the load calculated in Step 17 is less than the minimum calculated in Step 4, skip to Step 30.

Step 19. Calculate the maximum load that can be assigned to the steam turbines without using more steam than is potentially available, from the combination of excess exhaust and boilers. Set this value in the array used by routine LDIST.

Step 20. Calculate the steam turbine input requirement, to satisfy the load calculated in Step 17, by calling routine LDIST and the steam turbine simulation routine.

Step 21. Recalculate the steam turbine load as that load which, when deducted from the total load, results in the load to the fuel-consuming generators being large enough to provide sufficient excess exhaust steam output to meet the steam turbine input calculated in Step 20. This assumes that the excess steam output from the fuel-consuming generators will be proportional to the load and to the results of Step 15.

Step 22. If the load calculated in Step 21 is at least the minimum portion of the load that steam turbines may be allowed to meet, as calculated in Step 4, set the output variable PS for this much load.

Step 23. If the steam turbine input requirement calculated in Step 20 was based on operating a single unit of the smallest size steam turbine, or if this allocation reached the limit calculated in Step 19, skip to Step 30.

Step 24. Determine the next smaller possible steam turbine operating capacity, by setting the limit on operating capacity to slightly less than the operating capacity used in Step 20, and by calling LDIST.

Step 25. Estimate the steam input that would be required to operate the steam turbines optimally at this assignment, by using the average input-to-output ratio calculated in Step 9.

Step 26. Calculate the steam turbine load from the estimate of input determined in Step 25, using the method of Step 21.

Step 27. Re-estimate the excess exhaust steam by the method of Step 15.

Step 28. Re-estimate the steam turbine load from the excess exhaust steam estimate of Step 27, using the method of Step 21.

Step 29. If the load calculated in Step 28 is greater than the minimum load calculated in Step 4, set the result variable, PS, to this value, or retain its previous value, whichever is larger.

Step 30. Recalculate the available excess exhaust steam from the steam turbine load assignment (specified by the current value of the variable PS) using the method of Step 15.

Step 31. Recalculate the maximum assignable steam turbine operating capacity as the sum of the excess exhaust steam estimate from Step 30 (which may be negative) and the boiler total maximum capacity, divided by the estimated average input-to-output ratio of the steam turbines.

Step 32. If the remaining load can be met by fuel-consuming generators, skip to Step 35.

Step 33. Allocate to the steam turbine the load that cannot be met by fuel-consuming generators, subject to the limitations of (1) steam turbine capacity and (2) potentially available steam input.

Step 34. Recalculate the excess steam available and the steam turbine operating capacity constraint.

Step 35. Recalculate the estimated steam turbine input requirement, from the current value of the variable PS, and the estimated average input-to-output ratio.

Step 36. Allocate the remaining electric load between gas turbine generators and diesel engine generators by calling routine OPFUEL.

The routine assumes that the steam turbine is small and inefficient. Likewise, the routine assumes that, when there is a choice, the absorption chiller can better use any excess exhaust heat. As with all optimal allocation calculations in DOE-2, various approximations are used, most noteably linear extrapolation from test points. The results should be about as good as could be obtained in actual practice, but perhaps not for an application where the true optimum is desired to be known to a high degree of precision.

Routine OPFUEL

Routine OPFUEL allocates electric load between diesel engine- and gas turbine-driven generators.

This routine is called twice from routine OPELEC, once to obtain an estimate of how much exhaust steam will be available to run steam turbines and absorption chillers, and once for the final allocation of load after the steam turbine load has been decided. Some variables in OPFUEL will thus have different values in these two different circumstances. As an example, the amount of electric load to be allocated in the first case is the total load. In the second case, the amount of electric load is the load minus that to be satisfied by the steam turbines.

Routine OPFUEL contains the following assumptions:

1. Diesel engine-driven generators are more efficient than gas turbine-driven generators.

2. Because diesel engines have better part load performance than gas turbines, the combination of a gas turbine (or turbines) at optimum ratio and a diesel (or diesels) at partial loading is preferable to the combination of a gas turbine (or turbines) at partial loading and a diesel (or diesels) at higher load.

The algorithm used in this routine is as follows:

Step 1. Set the result variables to zero.

Step 2. If the total electric load is zero, or there are no fuel-consuming electric generators, return to the calling routine.

Step 3. Calculate the maximum and minimum portions of the load that may be assigned to the two generator types.

Step 4. If there are no gas turbines, or the portion of the total electric load to be allocated is within the maximum that the diesels can meet, or if the portion of the load to be allocated is less than the minimum that the gas turbines can meet, skip to Step 9.

Step 5. Set the gas turbine portion of the total electric load to that which cannot be met by the diesels, subject to the minimum and maximum gas turbine outputs.

Step 6. If the load allocated to the gas turbines in Step 5 is the maximum that can be allocated, or if it results in all of the gas turbines operating at their optimum or higher load ratio, skip to Step 9.

Step 7. Determine the operating capacity of the gas turbines required to meet the load allocated in Step 5, by calling routine LDIST.

Step 8. Increase the portion of the load allocated to gas turbines, to their optimum operating ratio times the operating capacity, determined in Step 7, if it is not already this high.

Step 9. If the portion of the load not met by the gas turbines is at least the minimum operating rate of the smallest diesel engine, then assign this remaining load to diesel engines.

The algorithm employed here is correct for the default values of performance functions in the routine and for small variations from these defaults. It seems unlikely that a plant would have a gas turbine more efficient than its diesel engines. This algorithm will not find the best solution if there is a circumstance in which operating a gas turbine at part load is perferable to operating a diesel at part load with the gas turbine at its optimum load.

2.2.8.2.3 Allocation to the Different Sizes of an Equipment Type (routine LDIST)

Routine LDIST allocates the total load on an equipment type to the individual units of equipment of that type. It is used in conjunction with the default equipment optimization routines, OPCOOL and OPELEC, for distributing cooling and electrical loads, and by the main plant routine for distributing the heating load. It is bypassed whenever the user is using LOAD-ASSIGNMENTS to allocate the loads directly to the equipment.

When deciding the number of each size to operate, the routine chooses the combination of sizes that comes as close to the optimum operating ratio (keyword OPERATING-RATIO), as is possible. The algorithm assumes that any combination of equipment sizes is allowable, and that the mix of the best combinations can vary hourly. The algorithm makes no attempt to keep using the equipment that was operating the hour before.

The number of possible combinations is

$$NCOMBS = [(KAVQ_1) * (KAVQ_2) * (KAVQ_3)] - 1 \qquad (V.103)$$

where $KAVQ_i = KAV_i + 1$. KAV_i in turn is the number of each size (i) of the equipment type in question; it corresponds to the keyword MAX-NUMBER-AVAIL in the PLANT-EQUIPMENT command.

The program constructs all NCOMBS possible combinations. As it constructs each combination, it checks to see if this combination comes closer to the optimum operating ratio than the combinations tested so far. If it does, the program stores this combination and tests all subsequent combinations against it. Once all combinations have been constructed and tested, the best combination is known, and the equipment type is ready to be simulated.

The mathematical theory of the combination construction algorithm is not presented here. The algorithm is presented below with a sample table showing the order in which the combinations are constructed.

Definition of Terms

$CNOMQ_i$ The available capacity of a single unit of a given size of equipment

$$CNOMQ_i = CNOM_i * RCAP$$

where $CNOM_i$ is the nominal size (keyword SIZE in the PLANT-EQUIPMENT command) and RECAP is the available capacity ratio for this equipment type calculated in routine CAPADJ. RCAP is always equal to 1.0, except for chillers whose capacities will vary with temperature.

CAPOPQ The total capacity of this equipment combination. It is the sum of the $CNOMQ_i$ in the combination.

NEQ The number of different sizes of the equipment (not the number of a given size).

The following steps are carried out for each possible combination:

. For I = 1 to NEQ
. MQ = No. of this combination
. $MX = MQ/KAVQ_I$
. $CAPOPQ = CAPOPQ + \{[MQ - (KAVQ_I * MX)] * CNOMQ_i\}$
. MQ = MX

Check to see if this is a better combination. If so, store it.

CAPOPQ becomes the total capacity of this equipment combination.

Note that the calculation for MX is an integer division, i.e., any digits to the right of the decimal are truncated. Table V.1 is an example of how the combinations are constructed. In the table, there are three different sizes (NEQ = 3), two units of each size, for a total of 26 different combinations.

TABLE V.1

EXAMPLE OF EQUIPMENT COMBINATIONS

	Combinations								
	Size 1	Size 2	Size 3						
KAV>	2	2	2						
KAVQ>	2	3	3	MQ			MX		
M NEQ=	1	2	3	NEQ= 1	2	3	NEQ= 1	2	3
1	1	0	0	1	0	0	0	0	0
2	2	0	0	2	0	0	0	0	0
3	0	1	0	3	1	0	1	0	0
4	1	1	0	4	1	0	1	0	0
5	2	1	0	5	1	0	1	0	0
6	0	2	0	6	2	0	2	0	0
7	1	2	0	7	2	0	2	0	0
8	2	2	0	8	2	0	2	0	0
9	0	0	1	9	3	1	3	1	0
10	1	0	1	10	3	1	3	1	0
11	2	0	1	11	3	1	3	1	0
12	0	1	1	12	4	1	4	1	0
13	1	1	1	13	4	1	4	1	0
14	2	1	1	14	4	1	4	1	0
15	0	2	1	15	5	1	5	1	0
–	–	–	–	–	–	–	–	–	–
26	2	2	2	26	8	2	8	2	0

2.3 Economic Calculations

Calculations related to the economics of plant equipment are made in the PLANT program. The first costs and subsequent replacement costs are combined to calculate the investment. Annual maintenance, periodic overhauls, and energy costs are combined to evaluate savings.

The present value of life-cycle costs are calculated for (1) purchase, installation, and maintenance of plant equipment, and (2) the fuel and electricity used by the facility. The results of these calculations are passed to the ECONOMICS program.

Variable List

Keywords	FORTRAN Variables	Engineering Variables	Description
DISCOUNT-RATE	A1,ALFCYC(1)	A	discount rate
	$EQCOST_1$	C_1	first cost for an equipment type
	$EQCOST_2$	C_2	present value of life cycle costs from consumables and annual maintenance for an equipment type
	$EQCOST_3$	C_3	sum of the replacement, minor overhaul, and major overhaul costs over the life cycle period
COST	UBLK(2,I,J)	$C_{b/unit}$	the list of costs per unit energy corresponding to the blocks of energy specified by keyword BLOCK
	X_B	C_B	the cost for this block of energy
	CONSUM	C_{cons}	annual consumables
CONSUMABLES		$C_{cons/hr}$	cost per hour of operation for consumables
	$ENCOST_i$	C_{ei}	present value of all the energy of the ith type consumed over the entire project life
FIRST-COST		C_{first}	initial cost of this type of equipment

Keywords	FORTRAN Variables	Engineering Variables	Description
	COST	C_{future}	the present value of a year's worth of energy of a given type consumed I_{yrs} years in the future
LABOR		C_{labor}	cost per hour of maintenance labor
	AMAINT	C_{maint}	yearly routine maintenance costs
MIN-MONTHLY-CHG	UDATA(4,J)	C_{min}	is the minimum monthly charge
MINOR-OVHL-COST		C_{minor}	the cost of a minor overhaul for a piece of equipment
	CSTM	C_{month}	monthly energy charge
MAJOR-OVHL-COST		$C_{ovhl\text{-}major}$	cost of a major overhaul for a type of equipment
PEAK-LOAD-CHG	UDATA(6,J)	$C_{p/unit}$	the cost in dollars per unit of peak energy
		C_{peak}	the cost of the average of this months peak and the peak load in dollars
UNIFORM-COST	UDATA(2,J)	C_Q	the dollars/billing-unit for energy
	$EQCOST_5$	C_{tot}	total equipment costs for a given size and type
	CST	C_{yr}	the yearly charges for each utility
	REPLAC	f	frequency at which an overhaul occurs
	F	F	number of equipment replacement or overhaul cycles in the project life
	ACL	F_{ac}	accumulative present value factor for labor over the entire project life

Keywords	FORTRAN Variables	Engineering Variables	Description
	ACM	F_{am}	accumulative present value factor for materials over the entire project life
UNIT	UDATA(1,J)	F_{bill}	the number of Btu's of energy per billing unit
	X	F_f	present value factor for a given energy type
INSTALLATION		F_{inst}	multiplier on the equipment FIRST-COST to estimate the installed first cost
	XLABOR	F_L	present value factor for labor
	XMAT	F_M	present value factor for materials
ESCALATION	UDATA(3,J)/100	I_f	fuel escalation rate relative to general inflation expressed as a fraction (I_f = ESCALATION/100)
LABOR-INFLTN	A2	I_L	labor inflation rate relative to general inflation expressed as a fraction (I_L = LABOR-INFLTN/100)
MATERIALS-INFLTN	R/100	I_M	materials inflation rate relative to general inflation (I_M = MATERIALS-INFLTN/100)
	IYEAR	I_{yr}	integer YEAR
MULTIPLIER	UBLK(1,I,J)	M	the multiplier of the monthly peak load that determines the number of energy units in the current block
	IYEARS	N_{yrs}	number of years
INSTALLED-NUMBER		N_{eq}	number of this type of equipment

Keywords	FORTRAN Variables	Engineering Variables	Description
		P_{costs}	present value of the annual costs that occurred during the year
	$OMPLAN_{IYEAR}$	P_{Iyr}	the present value of the overhaul and annual costs for the year specified by YR
	HO	t_{cycle}	the interval in hours to overhaul or replacement (equal to t_{life}, $t_{ovhl-minor}$, or $t_{ovhl-major}$)
	RH	t_{eq}	number of hours an equipment unit will operate over the life cycle period
MAINTENANCE		t_{maint}	the number of maintenance hours required each year for this equipment type
	$IOPRHR_{j,i}$	t_{op}	number of hours all equipment of this size operated during the simulated year
MAJOR-OVHL-INT		$t_{ovhl-major}$	the number of hours between major overhauls for a type of equipment
MINOR-OVHL-INT		$t_{ovhl-minor}$	the expected number of operating hours between minor overhauls
EQUIPMENT-LIFE		t_{life}	the number of operating hours from the time a piece of equipment is new until it must be replaced
	HI	t_{part}	hours left in a partial cycle at the beginning of a simulation period
HOURS-USED	HU	t_{used}	the number of hours a piece of equipment has been used at the beginning of the simulation

Keywords	FORTRAN Variables	Engineering Variables	Description
PROJECT-LIFE	E,CN	$T_{project}$	the length of the project in years
	Y1	T_{left}	the years remaining in the current overhaul or equipment replacement cycle
BLOCK	BLOK and/or UBLK(1,I,J) if BLOCK,COST method is used	Q_{block}	the block of energy currently being processed in energy units
	EMON	Q_{mon}	energy consumption in the units the energy will be billed in (therms, kwhs, gallons, etc.)
	ENPEAK	Q_{p-mo}	monthly peak load in Btus
		Q_{peak}	peak load that occurred during the year in Btus
MIN-PEAK-LOAD	UDATA(5,J)	$Q_{peak-min}$	the minimum peak load corresponding to a minimum demand surcharge
	ENUSE	Q_{used}	energy consumption in Btus
	X(1)	X_1	the present value of the equipment replacement costs incurred over the entire life cycle period
	X(2)	X_2	the present value of the minor overhaul costs incurred over the entire life cycle period
	YEAR	YR	the year in which an overhaul occurs
	PERIOD	τ	the number of years in each replacement or overhaul cycle
	SHIFT	Δ	the fraction of a cycle that occurred prior to the current simulation period

2.3.1 Equipment Costs (subroutines COSTEQ and DEFALT)

Subroutine COSTEQ calculates the life cycle costs of the equipment used in the simulation. Equipment life cycle costs include first costs, installation costs, annual maintenance, consumables exclusive of fuel (lubricants, etc.), minor overhauls, major overhauls, and replacement costs. If the user has cost data on one or more specific equipment units that he intends to simulate, the cost data should be entered directly using the keywords of the PLANT-EQUIPMENT command. If the user intends to allow the program to size equipment automatically and/or to calculate the equipment costs by default, he should examine the default values of the REFERENCE-COSTS command and determine whether they are appropriate. (Note that the REFERENCE-COSTS defaults are out of date and most likely are not appropriate.) The REFERENCE-COSTS are used to calculate the default costs of the various sizes of each equipment type input in the manner described in Sec. V.B.1 of the DOE-2.1A Reference Manual (Ref. 2). The calculation of default equipment costs is done in subroutine DEFALT.

Subroutine COSTEQ is called at the end of the PLANT simulation once the equipment hours of operation for various equipment types and sizes is known. Additional data used in the life cycle calculations are entered under the PLANT-COSTS command. The algorithm assumes that the equipment usage has been calculated for an entire year and, as a result, the equipment costs will be meaningless for a RUN-PERIOD less than one year in length.

Present value factors. The algorithm calculates equipment life cycle costs in terms of their present value. Several present value factors are pre-calculated for use in the life cycle calculations of the specific equipment units. The present value factor for labor costs is

$$F_L = \frac{1 + I_L}{1 + A} \tag{V.104}$$

where I_L is the labor inflation rate relative to general inflation (keyword LABOR-INFLTN) and A is the discount rate (keyword DISCOUNT-RATE). Similarly, the present value factor for materials is

$$F_M = \frac{1 + I_M}{1 + A} \tag{V.105}$$

where I_M is the material inflation rate relative to general inflation expressed as a fraction (keyword MATERIALS-INFLTN/100). These factors are used to find the present value of an expense that occurs N_{yrs} years in the future, as will be seen.

The accumulative present value factors for labor and materials over the entire project life are given by the formulas

$$F_{AL} = F_L * \frac{(1 - F_L{}^e)}{1 - F_L} \tag{V.106a}$$

and

$$F_{am} = F_m * \frac{(1 - F_m{}^e)}{1 - F_m} \tag{V.106b}$$

respectively. The exponent e is the number of years in the life cycle analysis. These factors are used to find the accumulated present value of expenses that occur during every year of the project life. The first cost, annual costs, and cyclical costs are calculated for each size of each equipment type.

First Cost. First costs are calculated for all types of equipment unless an existing building with existing equipment is being simulated. In this case, the user should set the HOURS-USED keyword to the number of operating hours already on the equipment. The installed first cost of each size is

$$C_1 = C_{first} * N_{eq} * F_{inst} \tag{V.107}$$

where C_{first} is the first cost (keyword FIRST-COST), N_{eq} is the number of installed units of this equipment (keyword INSTALLED-NUMBER), and F_{inst} is a multiplying factor to estimate the installed first-cost (keyword INSTALLATION).

Annual Costs. Annual costs consist of consumables and fixed maintenance costs. Consumables are calculated by multiplying the equipment-hours of operation each year by the dollars-per-hour of consumables used

$$C_{cons} = C_{cons/hr} * t_{op} \tag{V.108}$$

where t_{op} is the number of equipment-hours this equipment size operated (including multiple units of the same size) and $C_{cons/hr}$ is the cost per hour of operation of consumables (keyword CONSUMABLES). Routine maintenance costs are calculated as

$$C_{maint} = t_{maint} * C_{labor} * N_{eq}. \tag{V.109}$$

The present value of the life cycle costs from consumables and annual maintenance consists of the above quantities multiplied by their respective life cycle cost factors

$$C_2 = (C_{cons} * F_{am}) + (C_{maint} * F_{al}). \qquad (V.110)$$

Cyclical Costs. The equipment can have both minor and major overhauls at certain intervals, and the equipment may also need to be replaced at specified intervals. All intervals of cyclical costs are assumed to be in terms of the equipment-hours of operation, not in terms of years or other units independent of the hours the equipment operates.

The number of hours an equipment unit will operate over the life cycle period is

$$t_{eq} = t_{op} * \frac{T_{project}}{N_{eq}} \qquad (V.111)$$

where t_{op} is the total number of equipment hours equipment of this type and size operates in the year being simulated and $T_{project}$ is the length of the project in years (keyword PROJECT-LIFE).

The present value of the equipment replacement costs is

$$X_1 = C_1 * CYC(t_{life}, T_{project}, I_M, t_{eq}, t_{used}) \qquad (V.112)$$

where t_{life} is the number of hours a piece of equipment can operate before being replaced (keyword EQUIPMENT-LIFE) and t_{used} is the number of hours the equipment was used prior to this simulation (keyword HOURS-USED). The value of the function CYC includes both the number of replacements as well as the replacement's present value factors. Details of this function are presented in detail in Sec. V.2.3.2.

The present value of the minor overhauls is

$$X_2 = C_{minor} * N_{eq} * CYC(t_{ovhl-minor}, T_{project}, I_M, t_{eq}, t_{used}) \qquad (V.113)$$

where $t_{ovhl-minor}$ is the expected number of operation hours between minor overhauls (keyword MINOR-OVHL-INT), C_{minor} is the cost of a minor overhaul (keyword MINOR-OVHL-COST), and CYC() is the same function used in Eq. (V.112). X_2 is the present value of the minor overhaul costs incurred over the entire life cycle period. The present value of major overhaul is calculated in a manner identical to the minor overhaul calculation.

The total equipment costs for the life cycle period for a given size and type are

$$C_{TOT} = C_1 + C_2 + C_3. \qquad (V.114)$$

C_3 is the sum of the replacement, minor overhaul, and major overhaul costs over the life cycle period.

The ECONOMICS program also reports costs broken down by year. The following algorithm is used to calculate the present value of an overhaul that occurs at some year in the future.

a. The year (YR) in which the overhaul occurs is initialized to zero

$$YR = 0. \tag{V.115}$$

b. The frequency at which the overhaul occurs (in years) is

$$f = \frac{t_{ovhl-minor} * N_{eq}}{t_{op}} . \tag{V.116}$$

c. The future year in which the overhaul occurs is

$$YR = YR + f. \tag{V.117}$$

d. If YR is greater than the project life, $T_{project}$, (or up to a maximum of 25 years), then the overhaul is not necessary and this algorithm is ended. Otherwise, the present value of the overhaul is

$$P_{Iyr} = C_{ovhl-minor} * F_M{}^{YR} \tag{V.118}$$

where the subscript I_{yr} is simply YR rounded up to the next integer. Steps c and d are repeated until the conditions described in step d are satisfied.

The present value of major overhauls is calculated in a manner identical to the minor overhaul calculation except the keywords $t_{ovhl-major}$ and $C_{ovhl-major}$ are substituted where appropriate. P_{Iyr} is the sum of the overhaul costs calculated above for the particular year (Iyr) plus the present value of the annual costs that occur that year:

$$P_{Iyr} = P_{Iyr} + \left(C_{cons} * F_M{}^{Iyr}\right) + \left(C_{maint} * F_L{}^{Iyr}\right).$$

P_{Iyr} is then summed over all sizes and types of equipment.

2.3.2 Function CYC

This function calculates the cyclical cost coefficient used in routine COSTEQ, the equipment cost algorithm. The cyclical cost coefficient includes both the number of times the cyclical cost occurs and the present value factor of those costs. Inputs to this algorithm are

- t_{cycle}, the interval in hours to overhaul or replacement (keywords EQUIPMENT-LIFE, MINOR-OVHL-INT, MAJOR-OVHL-INT)
- $T_{project}$, the project life (PROJECT-LIFE),
- I_M, the material inflation rate (MATERIALS-INFLTN/100),
- t_{eq}, the number of hours the equipment will operate during the project life,
- t_{used}, the hours of operation on used equipment at the start of the project (HOURS-USED), and
- A, the discount rate (DISCOUNT-RATE).

Cyclical costs as defined in this algorithm can be minor overhauls, major overhauls, or equipment replacement. This algorithm is called separately for each type of cyclical cost. For the purpose of clarity, the overhaul or replacement interval will be referred to as a "cycle" in the following discussion.

Step 1

When simulating old equipment, the beginning of the life cycle period is usually in the middle of a cycle. The fraction of the cycle that occurred earlier than the period under consideration is

$$\Delta = \frac{t_{used}}{t_{cycle}} - \text{INT}\left[\frac{t_{used}}{T_{cycle}}\right] . \qquad (V.119)$$

The function INT() causes the real number expression to become integer (digits to the right of the decimal are dropped). Δ then becomes the fractional value that INT() dropped. Note that if t_{used} is greater than the cycle period ($t_{ovhl-minor}$ for example), one or more cycles may have already occurred before the start of the life cycle period. Costs of complete cycles that occurred previously are of no concern to this program. Δ is needed to calculate when the next cycle cost of this project life is encountered. Note that $\Delta = 0$ for new equipment.

The hours left in this cycle at the beginning of the life cycle period is

$$t_{part} = t_{cycle} * (1.0 - \Delta). \qquad (V.120)$$

Step 2

The number of cycles in the project life is

$$F = \mathrm{INT}\left[\frac{t_{eq}}{t_{cycle}} + \Delta\right]. \tag{V.121}$$

The function INT() again causes the argument to be rounded down to an integer value. Because the cyclical cost comes at the end of the cycle, a fraction of a cycle at the end of the life cycle period has no cost associated with it.

Step 3

The number of years per cycle is

$$\tau = \frac{T_{project}}{\left[\frac{t_{eq}}{t_{cycle}}\right]} \tag{V.122}$$

Step 4

The years left in the current cycle are

$$T_{left} = T_{project} * \frac{t_{part}}{t_{eq}} . \tag{V.123}$$

Step 5

The present value factor is

$$F_m = \frac{1 + I_M}{1 + A} . \tag{V.124}$$

Step 6

The cyclical cost coefficient is calculated using the formula

$$CYC = Y^{T_{left}} * \left[1.0 + \frac{Y^{\tau} - Y^{\tau F}}{1.0 - Y} \right]. \qquad (V.125a)$$

If $Y^{\tau} = 1.0$, then CYC = F. (V.125b)

2.3.3 Energy Costs (subroutine COSTEN)

Subroutine COSTEN calculates the costs of the energy types being used in the simulation. The yearly cost data is entered through the keywords under the ENERGY-COST command. The life cycle costing of the energy also uses some of the data entered under the PLANT-COSTS command. The algorithm calculates the cost based on a minimum monthly charge (keyword MIN-MONTHLY-CHG), a monthly energy charge, and monthly demand charge (keyword PEAK-LOAD-CHG), if one applies. Since the program simulates the building and plant in time steps of one hour, the demand cannot be calculated for an interval of less than one hour. The energy cost may be calculated based on a rate that remains constant regardless of the total monthly amount used (keyword UNIFORM-COST), blocks of energy that have different costs (keyword BLOCK, COST pairs), or blocks of energy whose size varies with the monthly demand (keyword MULTIPLIER, COST pairs). The latter category includes the KWh/kW rate schedule that many power companies use.

This routine is called at the end of the PLANT simulation once the year's energy usage is known. The algorithm assumes that the energy usage has been calculated for an entire year and the energy costs will be meaningless for a RUN-PERIOD less than one year in length. Steps 1 - 6 are repeated for every month of the simulation for each energy type to determine the energy costs for the first year. Step 7 is repeated for each energy type to calculate life cycle costs.

Step 1

During the hourly simulation, the program calculates all energy consumption in units of Btus (Q_{used}). The first step in calculating monthly energy costs is to convert the energy into the units the energy will be billed in.

$$Q_{mon} = \frac{Q_{used}}{F_{bill}} \qquad (V.126)$$

where F_{bill} is the number of Btus per billing unit and is input through the keyword UNIT.

Step 2

If a uniform cost applies to this energy type, the monthly energy charge is

$$C_{month} = Q_{mon} * C_Q. \qquad (V.127)$$

C_Q is the dollars/billing-unit and corresponds to the keyword UNIFORM-COST.

Step 3

If the energy charge is being calculated in blocks, the following steps are repeated until no more blocks remain, or no energy remains unallocated to a block.

a. Q_{block} is the block of energy currently being processed. It corresponds to the keyword BLOCK and produces the list of values the user input as successive blocks are processed.

b. The cost for this block of energy is

$$C_B = Q_{block} * C_{b/unit} \qquad (V.128)$$

where $C_{b/unit}$ produces the list of block costs input through the keyword COST as each block of energy is processed.

c. The energy as yet unallocated to a block is

$$Q_{mon} = Q_{mon} - Q_{block}.$$

d. In Step 3b, if the energy filling this block is less than the size of the block ($Q_{mon} < Q_{block}$,) then Q_{mon} is used in place of Q_{block}. If all the blocks have been filled and there is still energy remaining to be put into a block, the remaining energy is put into the last block. The total energy charge is the sum of the charges in each block

$$C_{month} = \Sigma C_B.$$

Step 4

If the energy charges are being calculated in terms of MULTIPLIERs, the procedure is identical to the one above except for Eq. (V.128), where the block size is calculated as

$$Q_{block} = M * \frac{Q_{p-mo}}{F_{bill}} \qquad (V.129)$$

where Q_{p-mo} over F_{bill} is the monthly peak converted from Btu's to the proper billing unit. M corresponds to the appropriate value in the list of the MULTIPLIER keyword. The list of costs are entered through the COST keyword as before.

Step 5

The peak load is calculated based on the average of this month's peak, Q_{p-mo}, and the maximum peak that occurred during the year, Q_{peak}, or the minimum peak load (keyword MIN-PEAK-LOAD), whichever is larger

$$C_{peak} = \frac{[.5 * (Q_{p-mo} + Q_{peak})]}{F_{bill}} * C_{p/unit} \qquad (V.130a)$$

or

$$C_{peak} = Q_{peak-min} * C_{p/unit} \qquad (V.130b)$$

whichever is larger. F_{bill} again converts Btus into the appropriate billing units, $C_{p/unit}$ is the unit cost of peak energy and corresponds to the keyword PEAK-LOAD-CHG, and $Q_{peak-min}$ is the minimum peak energy that corresponds to a minimum demand surcharge (keyword MIN-PEAK-LOAD).

Step 6

Finally, the monthly charge is increased by the peak load charge. A check is made to ensure that the monthly charge is above the minimum monthly charge

$$C_{month} = C_{month} + C_{peak} \qquad (V.131a)$$

or

$$C_{month} = C_{min} \qquad (V.131b)$$

whichever is larger. C_{min} is the minimum monthly charge (keyword MIN-MONTHLY-CHG).

The yearly charges for each utility are the sum of the monthly charges

$$C_{yr} = \Sigma C_{month}. \tag{V.132}$$

Step 7

The ECONOMICS subprogram needs the present value of the energy costs for each year of the PROJECT-LIFE. The present value factor for a given energy type is

$$F_f = \frac{1 + I_f/100}{1 + A/100} \tag{V.133}$$

where I_f is the energy cost's escalation rate (percent) relative to general inflation (keyword ESCALATION), and A is the discount rate in percent (keyword DISCOUNT-RATE).

The present value of a year's worth of energy of a given type consumed I_{yrs} in the future is

$$C_{future} = C_{yr} * F_f^{Iyr}. \tag{V.134}$$

The present value of all the energy of this type consumed over the entire project life is either

$$C_{ei} = \sum^{T_{project}} C_{future} \tag{V.135}$$

or can be calculated directly using the formula

$$C_{ei} = C_{yr} * \frac{F_f * \left(1 - F_f^{T_{project}}\right)}{1 - F_f}. \tag{V.136}$$

Equation (V.136) is the form used in this program.

The life cycle energy costs are reported in the plant reports and are also used in the ECONOMICS program.

4. CHAPTER V REFERENCES

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5. CHAPTER V INDEX (for non-solar equipment)*

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VI. ECONOMICS SIMULATOR

TABLE OF CONTENTS

1. DESCRIPTION OF THE LIFE-CYCLE COSTING METHODOLOGY USED IN DOE-2
by Frederick C. Winkelmann

1.1 Concept of Life-Cycle Cost

The economics calculations done in DOE-2 use the life-cycle costing methodology described in the DOE manual ERDA-76/130 (Ref. 1). In the life-cycle costing method, the present value of the capital, operation and maintenance, and energy costs of a building are calculated over the life-cycle of the building. For comparison of alternatives and retrofits, a few numbers, called "investment statistics", are also calculated. These statistics measure the cost-effectiveness of an alternative design compared to a reference or "baseline" case.

Cost calculations are made in both the PLANT and ECONOMICS programs. The PLANT program calculates energy costs and plant (primary) equipment capital and operating costs. The corresponding input data are entered in PDL using the PLANT-EQUIPMENT, PLANT-COSTS, and REFERENCE-COSTS instructions. PLANT passes the following information to ECONOMICS:

* a. Discount rate (%)
* b. Labor inflation rate (%)
* c. Materials inflation rate (%)
* d. Project lifetime (yrs)
* e. Labor cost ($/hr)
* f. Plant equipment first cost ($)
** g. Life-cycle cost for replacing plant equipment ($)
** h. Annual energy use at the site (Btu)
** i. Annual energy use at the source (Btu)
** j. Present value of energy cost for each year of the project lifetime ($)
** k. Present value of plant operating costs for each year of the project lifetime ($).

Costs for non-plant components, which can include secondary systems, insulation, control systems, solar collectors, etc., are calculated in the ECONOMICS program. Cost data for these items are entered by the user in EDL using COMPONENT-COST instructions. In the following, non-plant costs are sometimes referred to as "building costs" to distinguish them from plant costs.

ECONOMICS adds plant costs and building costs to arrive at an overall life-cycle cost. It also computes the following economic measures or "investment statistics":

a. investment,
b. energy and non-energy cost savings,
c. energy use savings,
d. ratio of total cost savings to investment,
e. ratio of energy use savings to investment, and
f. discounted payback period.

* = specified by user in PDL.
** = calculated by PLANT.

These quantities are calculated by comparing costs and energy use for the project under analysis (called "the alternative") with those input by the user for a baseline case.

1.2 Life-Cycle Costing Methodology.

In this section, a description is given of the terminology and methodology used in the life-cycle cost calculations.

The project lifetime or analysis period is the period, in years, over which the life-cycle cost analysis is made. In DOE-2, this can be between 1 and 25 years and is specified in PDL. The life-cycle cost is the total cost of an item over the project lifetime. For a cost that recurs every year, such as an energy cost, the life-cycle cost (LCC) is

$$LCC = \sum_{n=1}^{NY} C_n,$$

where NY is the project lifetime, in years, and C_n is the cost, in dollars, in the nth year.

Rather than use the actual cost in year n, the program calculates the present value of the cost, which is given by

$$C_n \text{ (present value)} = C \left(\frac{1 + i}{1 + d}\right)^n, \qquad \text{(VI.1)}$$

where C is the cost in constant dollars, i is the cost inflation rate (relative to general inflation), and d is the discount rate (relative to general inflation).

By "constant dollars" is meant dollars that have not been adjusted for the effects of future inflation. They are dollars as of the start of the analysis period. The "cost inflation rate" is the fraction by which the cost is expected to increase each year over and above the general inflation rate. (It is, thus, a "real" or "differential" rate). The "discount rate" is the rate of interest (over and above the general infaltion rate) that money would be expected to receive if it was loaned on the free market. Like the cost inflation rate, the discount rate specified in DOE-2 should be a real or differential rate. Thus, if money can be lent at 18 percent and the general inflation rate is 12 percent, the discount rate is 0.18 - 0.12 = 0.06.

As an illustration of Eq. (VI.1), consider the following example. If

Project lifetime = 25 years
Discount rate = 10 percent (above general inflation)
Energy inflation rate = 5 percent (above general inflation)
C = $1000 (annual energy cost cost in constant dollars),

then, the present value of the energy cost in year 10, say, would be

$$C_{10} \text{ (present value)} = \$1000 \left(\frac{1 + 0.05}{1 + 0.10}\right)^{10}$$

$$= \$1000 \ (0.955)^{10}$$

$$= \$1000 \ (0.628)$$

$$= \$628.$$

The present value of the energy cost over the project lifetime would be

$$LCC = \sum_{n=1}^{25} C \left(\frac{1 + i}{1 + d}\right)^{n}$$

$$= \sum_{n=1}^{25} 1000 \left(\frac{1.05}{1.10}\right)^{n}$$

$$= 1000 \sum_{n=1}^{25} (.955)^{n}$$

$$= 1000 \ (14.436)$$

$$= \$14,436.$$

Note that without discounting (i.e., without present-valuing), the life-cycle cost would simply be 25 x \$1000 = \$25,000. The quantity 14.436 above is called the present value factor. It will be equal to the project lifetime only if i = d.

1.3 Cost Types

In DOE-2, non-energy costs are broken down into three categories:

a. first cost,
b. operation and maintenance cost, and
c. replacement cost.

The first cost is the purchase price of a component, including installation. Operation and maintenance cost includes expenses required to keep the component in working condition. Operation and maintenance cost is further broken down into annual costs, which (in constant dollars) are the same each year, and costs for minor and major overhauls. The replacement cost is the capital cost (including installation) of replacing a component at the end of its useful life.

The program calculates the life-cycle cost associated with categories a, b, and c, then combines these costs to arrive at the overall life-cycle cost of an item. The next section shows in detail how this is done.

1.4 Calculation of Overall Cost for a Component

Table VI.1 gives the input data that are used to calculate the life-cycle cost of a building component.

TABLE VI.1

INPUT DATA USED TO CALCULATE LIFE-CYCLE COSTS OF A BUILDING COMPONENT

Specified In	Keyword	Definition	Variable Name*
EDL	NUMBER-OF-UNITS	Number of identical units of the component (e.g., number of sq. ft.).	U
EDL	FIRST-COST	Unit first cost ($) excluding installation.	FC
EDL	INSTALL-COST	Unit installation cost ($).	CI
EDL	ANNUAL-COST	Unit operations cost ($) that occurs on a regular, annual basis (excludes overhauls).	AC
EDL	MIN-OVHL-COST	Unit cost for minor overhaul ($).	CMIN
EDL	MAJ-OVHL-COST	Unit cost for major overhaul ($).	CMAJ
EDL	MIN-OVHL-INT	Time in years between minor overhauls.	AM_1
EDL	MAJ-OVHL-INT	Time in years between major overhauls.	AM_2
EDL	COMPONENT-LIFE	Useful lifetime of component, in years.	EQLIFE
PDL	PROJECT-LIFE	Project life (analysis period), in years.	NY
PDL	DISCOUNT-RATE	Discount rate (%).	DR
PDL	LABOR-INFLTN	Cost inflation rate for labor (%).	RL
PDL	MATERIALS-INFLN	Cost inflation rate for materials (%).	RM

*If a cost, after multiplication by NUMBER-OF-UNITS.

The present value of the first, operation and maintenance, and replacement costs are calculated as follows. The calculations are done in subroutine NPCOST.

1.4.1 First cost

It is assumed the intial purchase and installation of the component occurs at the beginning of the analysis period. The present value of the first cost is thus

$$(FC + CI) * \left(\frac{1 + RM * 100}{1 + DR * 100}\right)^0 = FC + CI.$$

1.4.2 Replacement cost

Replacements occur every EQLIFE years. If EQLIFE $\geq$ NY, there are no replacements. Otherwise, the present value of all replacement costs is

$$CREPPV = \left[FC * PVF\ (RM,\ DR,\ NY,\ EQLIFE)\right] + \left[CI * PVF\ (RL,\ DR,\ NY,\ EQLIFE)\right],$$

where PVF is the "present value factor", calculated by Function PVF, and defined as follows.

1.4.3 Present value factor

For cost escalation rate R, discount rate D, analysis period Y, and compounding interval T,

$$PVF\ (R,\ D,\ NY,\ T) = \sum_{n=1}^{NMAX} \left(\frac{1 + R}{1 + D}\right)^{nT}, \qquad (VI.2)$$

where NMAX, the number of times the cost occurs in project lifetime NY, is given by

$$NMAX = int(NY/T).$$

Defining $x = \left(\frac{1 + R}{1 + D}\right)^T$, Eq. (VI.2) becomes

$$PVF\ (R,\ D,\ NY,\ T) = \sum_{n=1}^{NMAX} x^n. \qquad (VI.3)$$

For $x = 1$ (i.e., $R = D = 0$), PVF = NMAX. For $x \neq 1$, the summation on the right hand side of Eq. (VI.3) can be simplified, yielding

$$PVF = \frac{x(1 - x^{NMAX})}{1 - x} .$$

1.4.4 Annual cost

The present value of the annual cost in year j is

$$ACPV_j = AC\left(\frac{1 + RL * 100}{1 + DR * 100}\right)^j , \; 1 \leq j \leq NY.$$

Note that the cost inflation rate used is that for labor, RL, under the assumption that the dominant contribution is the labor involved in maintenance. The life cycle annual cost is

$$\sum_{j=1}^{NY} ACPV_j .$$

1.4.5 Minor overhaul cost

If a minor overhaul is required every AM_1 years, there will be $NMAX_1 = int(NY/AM_1)$ minor overhauls during the project lifetime. If each overhaul costs CMIN in constant dollars, the present value of the kth overhaul is

$$CMINPV_k = CMIN\left(\frac{1 + RL * 100}{1 + DR * 100}\right)^{k * AM_1} , \; 1 \leq k \leq NMAX_1 .$$

The life cycle cost for minor overhauls is

$$\sum_{n=1}^{NMAX_1} CMINPV_k .$$

If a minor overhaul occurs right at the end of the project lifetime, it is neglected.

1.4.6 Major overhaul cost

Major overhauls are treated just like minor overhauls, except that the interval, AM_2, between major overhauls is greater than the minor overhaul interval AM_1. Thus, if a major overhaul costs CMAJ in constant dollars, then the present value of the kth major overhaul is

$$CMAJPV_k = CMAJ \left(\frac{1 + RL * 100}{1 + DR * 100} \right)^{k * AM_2}, \; 1 \le k \le NMAX_2.$$

where $NMAX_2 = int(NY/AM_2)$. The life-cycle cost for major overhauls is

$$\sum_{k=1}^{NMAX_2} CMAJPV_k.$$

If a major overhaul occurs right at the end of the project lifetime, it is neglected.

If a minor and major overhaul occur at the same time (for example, if $AM_1 = 0.5$ and $AM_2 = 2.0$, the fourth minor overhaul and first major overhaul occur at the end of the second year), the costs are added.

1.4.7 Overall life-cycle cost

The overall life-cycle cost, CTOTPV, of a building component is the sum of the first, replacement, annual, and overhaul costs:

$$CTOTPV = [FC + CI] + CREPPV + \sum_{L=1}^{NY} ACPV_K + \sum_{k=1}^{NMAX_1} CMINPV_k + \sum_{k=1}^{NMAX_2} CMAJPV_k.$$

1.4.8 Salvage value and residual value

In DOE-2, the salvage value of a building component at the end of its useful life is neglected. This is because of the large uncertainty of assigning a realistic salvage value, even to the extent of knowing whether this value will be positive or negative. Likewise, residual value, which accounts for the unused life of a component at the end of the project lifetime, is neglected.

1.5 Calculation of Investment Statistics

The ECONOMICS program calculates several energy-use and dollar related quantities that are useful in deciding whether an investment in energy conservation is cost-beneficial. These quantities are:

(1) life-cycle energy cost savings,
(2) life-cycle operation and maintenance cost savings,
(3) total life-cycle cost savings [sum of (1) and (2)],
(4) investment,
(5) incremental investment,
(6) savings-to-incremental-investment ratio (SIR),
(7) discounted payback period,
(8) annual energy consumption savings at the site and at the source, and
(9) ratio of life-cycle energy savings (at the site and at the source) to incremental investment; this is the energy saved per dollar invested.

This section defines these quantities and describes how they are calculated. The calculations are done in subroutine SCOST. Table VI.2 gives the input data that are used to calculate the investment statistics.

1.5.1 Life-cycle savings in energy cost

The life-cycle savings in energy cost is:

$$ECSTOT = \sum_{i=1}^{NY} (ECBASE_i - EC_i),$$

where

$ECBASE_i$ = the present value of energy cost for the baseline case in year i,

EC_i = the present value of energy cost for the alternative case in year i, and

NY = the project lifetime, $1 \leq NY \leq 25$ years.

TABLE VI.2

INPUT DATA USED TO CALCULATE
INVESTMENT STATISTICS

Specified In	Keyword	Definition	Variable Name
PDL	PROJECT-LIFE	Project life (analysis period), in years.	NY
EDL	ENERGY-COST	Present value ($) of baseline energy cost for each year of the project life ($1 \leq i \leq NY$).	$ECBASE_i$
EDL	OPERATIONS-COST	Present value ($) of baseline operation and maintenance cost for each year of the project life ($1 \leq i \leq NY$), for plant and non-plant components.	$OMBASE_i$
EDL	REPLACE-COST	Life-cycle baseline replacement cost ($) of plant and non-plant components.	RCBASE
EDL	ENERGY-USE-SITE	Annual site energy use (Btu) of baseline.	EUBASE
EDL	ENERGY-USE-SRC	Annual source energy use (Btu) of baseline.	EUSBASE

1.5.2 Life-cycle savings in operation and maintenance cost

The life-cycle savings in operation and maintenance cost is:

$$OMSTOT = \sum_{i=1}^{NY} (OMBASE_i - OMTOT_i),$$

where

$OMBASE_i$ = the present value of the baseline operation and maintenance cost in year i, and

$OMTOT_i$ = the present value of operation and maintenance cost for the alternative case in year i.

1.5.3 Total life-cycle cost savings

The total life-cycle cost savings is

$$TOTS = ECSTOT + OMSTOT$$

1.5.4 Investment

The investment, TINV, is now calculated by summing the first cost and present value of the replacement cost for all plant and building items:

$$TINV = FCPLAN + RCPLAN + \sum_{i=1}^{NPC} (FC_i + CI_i + CREPPV_i).$$

where

FCPLAN	=	the total first cost (in constant dollars) of plant equipment, including installation,
RCPLAN	=	the life-cycle cost of plant equipment, including replacements,
FC_i	=	the first cost of the ith building component in constant dollars,
CI_i	=	the installation cost of the ith building component in constant dollars,
$CREPPV_i$	=	the life-cycle replacement cost, including installation, of the ith building component, and
NPC	=	the total number of building components.

1.5.5 Incremental investment

The incremental investment is the investment less the sum of the baseline first cost and the life-cycle replacement cost:

$$PVI = TINV - (FCBASE + RCBASE).$$

1.5.6 Savings-to-incremental-investment ratio

The savings-to-incremental-investment ratio (SIR) is the life-cycle savings divided by the incremental investment:

$$SIR = TOTS/PVI.$$

SIR is set to zero if PVI is zero. In general, an investment is cost-beneficial only if the savings generated over the life cycle exceeds the incremental investment, i.e., SIR > 1.0.

1.5.7 Discounted payback period

The discounted payback period, PAYBAC, is the number of years it takes the present value of accumulated savings to equal the incremental investment, PVI. PAYBAC is calculated as follows:

(1) If life-cycle savings, TOTS, is ≤ 0, PAYBAC is undefined; the program sets it to 999.

(2) If the incremental investment is ≤ 0, PAYBAC is set to zero.

(3) If TOTS < PVI, PAYBAC = (PVI/TOTS)NY; in this case, the payback period is longer than the analysis period.

(4) Otherwise, the program calculates PAYBAC by summing the present value of annual cost savings, $TOTSAV_i$, until the sum reaches PVI.

The steps are as follows:

1. Calculate p such that

$$\sum_{i=1}^{p} TOTSAV_i \leq PVI,$$

and

$$\sum_{i=1}^{p+1} TOTSAV_i > PVI;$$

2. then

$$PAYBAC = p + \left[\frac{PVI - \sum_{i=1}^{p} TOTSAV_i}{TOTSAV_{p+1}} \right].$$

1.5.8 Annual energy savings

The annual energy consumption savings, in Btu, at the site, EUSAV, and at the source, EUSSAV, are calculated next. These are simply:

EUSAV = EUBASE - EU

and

EUSSAV = EUSBAS - EUS,

where

EUBASE = the annual site energy consumption of the baseline,
EUBAS = the annual source energy consumption of the baseline,
EU = the annual site energy consumption of the alternative, and
EUS = the annual source energy consumption of the alternative.

1.5.9 Energy-savings-to-investment ratio

Finally, the program calculates the life-cycle savings-to-incremental-investment ratio (in Btu/$) at the site, EUSPVI, and at the source, EURPVI, according to:

EUSPVI = (EUSAV*NY)/PVI,

EURPVI = (EUSSAV*NY)/PVI.

1.6 Subroutine Description

RDESF	reads Economics Standard File and converts baseline energy use input from 10^6 Btu to Btu.
RDPCF	reads cost information file passed from PLANT.
EVRPT	prints EV-A report that contains summary of (a) cost information from PLANT, and (b) building component cost input data.
NPCOST	calculates present value of costs associated with building (non-plant) components. Calculation procedure is described in Sec. VI.1.4.
PVF	calculates the present value factor given a cost escalation rate, discount rate, number of years, and compounding interval. Calculation procedure is described in Sec. VI.1.4.
SCOST	calculates energy and operation/maintenance cost savings, total savings, and investment statistics according to procedure described in Sec. VI.1.5.
EORPT	prints three reports: (a) ES-A, summary of annual energy and operation/maintenance costs and savings relative to baseline; (b) ES-B, summary of building and plant non-energy costs; and (c) ES-C, summary of energy savings relative to baseline, investment statistics, and overall life-cycle costs.

2. CHAPTER VI REFERENCES

1. "Life-Cycle Costing, Emphasizing Energy Conservation," Energy Research and Development Administration Report ERDA 76/130, September 1976 (Revised May 1977). Available from the National Technical Information Service, U.S. Department of Commerce, 5285 Port Royal Road, Springfield, VA 22161.

3. CHAPTER VI INDEX (See also economics section of PLANT chapter)

*All page numbers are to be preceeded by "VI."

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(III.2.9)

Lawrence Berkeley Laboratory
UNIVERSITY OF CALIFORNIA

ENERGY & ENVIRONMENT DIVISION

DAYLIGHTING CALCULATION IN DOE-2

F.C. Winkelmann

May 1983

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May 1983

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ABSTRACT

Lighting accounts for about 20% of total electrical energy consumption in the United States. Using natural lighting is a cost-effective way to reduce this consumption and, at the same time, enhance the quality of the indoor environment. For several years, architects and engineers have used scale models, hand calculator programs, and sophisticated main-frame computer programs (such as LUMEN-II) to determine levels of interior daylight for different building configurations. However, none of these tools determines the annual energy savings from daylighting, information which could have an important effect on design decisions.

For this reason, a daylighting simulation has been added to DOE-2. Taken into account are such factors as window size, glass transmittance, inside surface reflectances of the space, sun-control devices such as blinds and overhangs, and the luminance distribution of the sky. Because this distribution depends on the position of the sun and the cloudiness of the sky, the calculation is made for standard clear- and overcast-sky conditions and for a series of 20 solar altitude and azimuth values covering the annual range of sun positions. The calculations are performed prior to the complete simulation, and the the resulting daylight factors are stored for later use. Analogous factors for glare are also calculated and stored.

For the hourly envelope simulation, the illuminance from each window is found by interpolating the stored daylight factors (using the current-hour sun-position and cloud cover), then multiplying by the current-hour exterior horizontal illuminance. If the glare-control option has been specified, the program will automatically close window blinds or drapes to decrease glare below a pre-defined comfort level. Adding the illuminance contributions from all the windows gives the total number of footcandles at each reference point.

This report describes the equations and algorithms used to perform the daylighting calculations in DOE-2.1B, and is intended as a supplement to the <u>DOE-2 Engineers Manual</u>, Version 2.1A, LBL-11353. Supporting user documentation may be found in the <u>DOE-2 Reference Manual</u>, LBL-8706, Rev.2, LA-7689-M, Ver. 2.1A, the <u>DOE-2 BDL Summary</u>, LBL-8688, Rev.3, the <u>DOE-2 Users Guide</u>, LBL-8689, Rev.2, the <u>DOE-2 Sample Run Book</u>, LBL-8678, Rev.1, and the <u>DOE-2 Supplement</u>, LBL-8706, Rev.3.Suppl.

ACKNOWLEDGMENT

The DOE-2 daylighting calculation was developed as a result of a collaboration between the LBL Building Energy Simulation Group (under the direction of James J. Hirsch) and Stephen Selkowitz of the LBL Windows and Daylighting Group. Valuable discussions and information were provided by Eliyahu Ne´eman, LBL/Technion (daylight availability), Francis Rubinstein, LBL (lighting controls), Gary Gillette, NBS/National Fenestration Council (daylight availability), and W. Frederick Buhl, LBL (DOE-2 structure). The program was tested by Bruce Birdsall (LBL), Steven Gates (California Energy Commission), Paul Hirsch (Argonne National Laboratory), and Richard Johnson (LBL). Mojtaba Navvab and J. J. Kim (LBL) helped in the validation of the program. Editing, word processing, and coordination of the program documentation, including this report, were accomplished by Karen H. Olson and Kathleen Ellington.

DAYLIGHTING CALCULATION IN DOE-2

Table of Contents

DAYLIGHTING CALCULATION IN DOE-2

1. Introduction

The DOE-2.1B daylighting model, in conjunction with the thermal loads analysis, determines the energy impact of daylighting strategies based upon hour-by-hour analysis of daylight availability, site conditions, window management in response to sun control and glare, and various lighting control strategies.

The daylighting calculation has three main stages. In the first stage (which is flow-charted in Table 1) a preprocessor calculates daylight factors for later use in the hourly loads calculation. The user specifies the coordinates of one or two reference points in a space. DOE-2 then integrates over the area of each window to obtain the contribution of direct light from the window to the illuminance at the reference points, and the contribution of light which reflects from the walls, floor, and ceiling before reaching the reference points. Taken into account are such factors as the luminance distribution of the sky, window size and orientation, glass transmittance, inside surface reflectances, sun control devices such as drapes and overhangs, and external obstructions. The calculation is carried out for standard CIE clear and overcast sky conditions for a series of 20 different solar altitude and azimuth values covering the annual range of sun positions. Analogous daylight factors for discomfort glare are also calculated and stored.

In stage two (see flow-chart Table 2) an hourly daylighting calculation is performed every hour that the sun is up. The illuminance from each window is found by interpolating the stored daylight factors using the current-hour sun position and cloud cover, then multiplying by the current-hour exterior horizontal illuminance. If the glare-control option has been specified, the program will automatically close window blinds or drapes in order to decrease glare below a pre-defined comfort level. A similar option uses window shading devices to automatically control solar gain.

In stage three, the program simulates the lighting control system (which may be either stepped or continuously dimming) to determine the electrical lighting energy needed to make up the difference between the daylighting level and the design illuminance. Each thermal zone can be divided into two independently controlled lighting zones. Finally, the zone lighting electrical requirements are passed to the thermal calculation which determines hourly heating and cooling loads.

The illuminance calculation has been validated by comparing DOE-2 predictions with scale-model measurements made in the LBL Sky Simulator and with SUPERLITE, a very detailed illuminance program. The results are shown and discussed in Ref. 1. Good agreement is observed among the three methods except far from the window-wall in side-lit geometries where the spilt-flux method used in DOE-2 overpredicts the inter-reflected illuminance.

The daylighting model in DOE-2.1B has been designed with future expansion in mind. At the present time, the program calculates interior illuminance for conventional window designs using a preprocessor

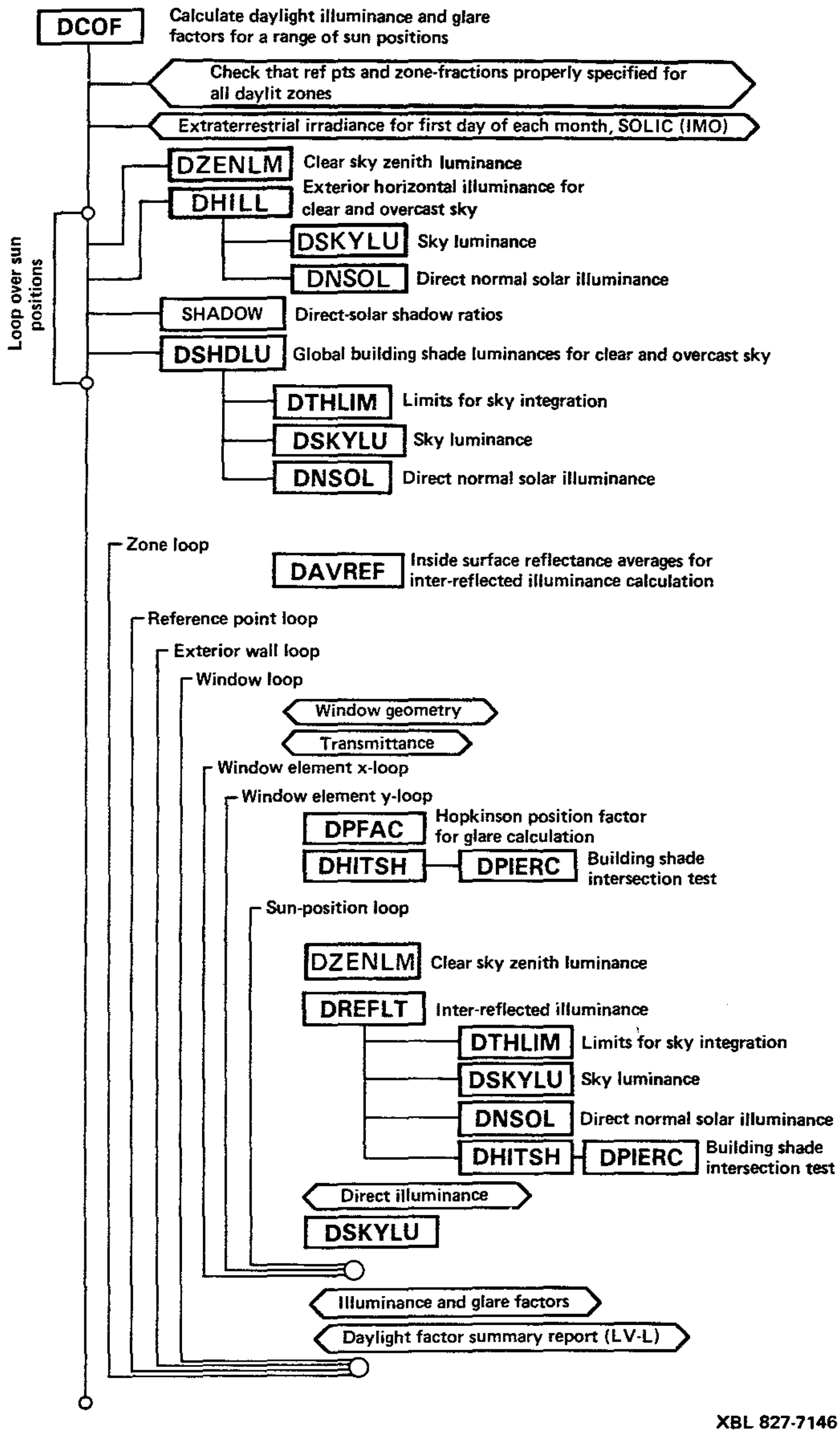


Table 1. DOE-2.1B daylighting preprocessor flowchart. Daylighting subroutines are in boldface.

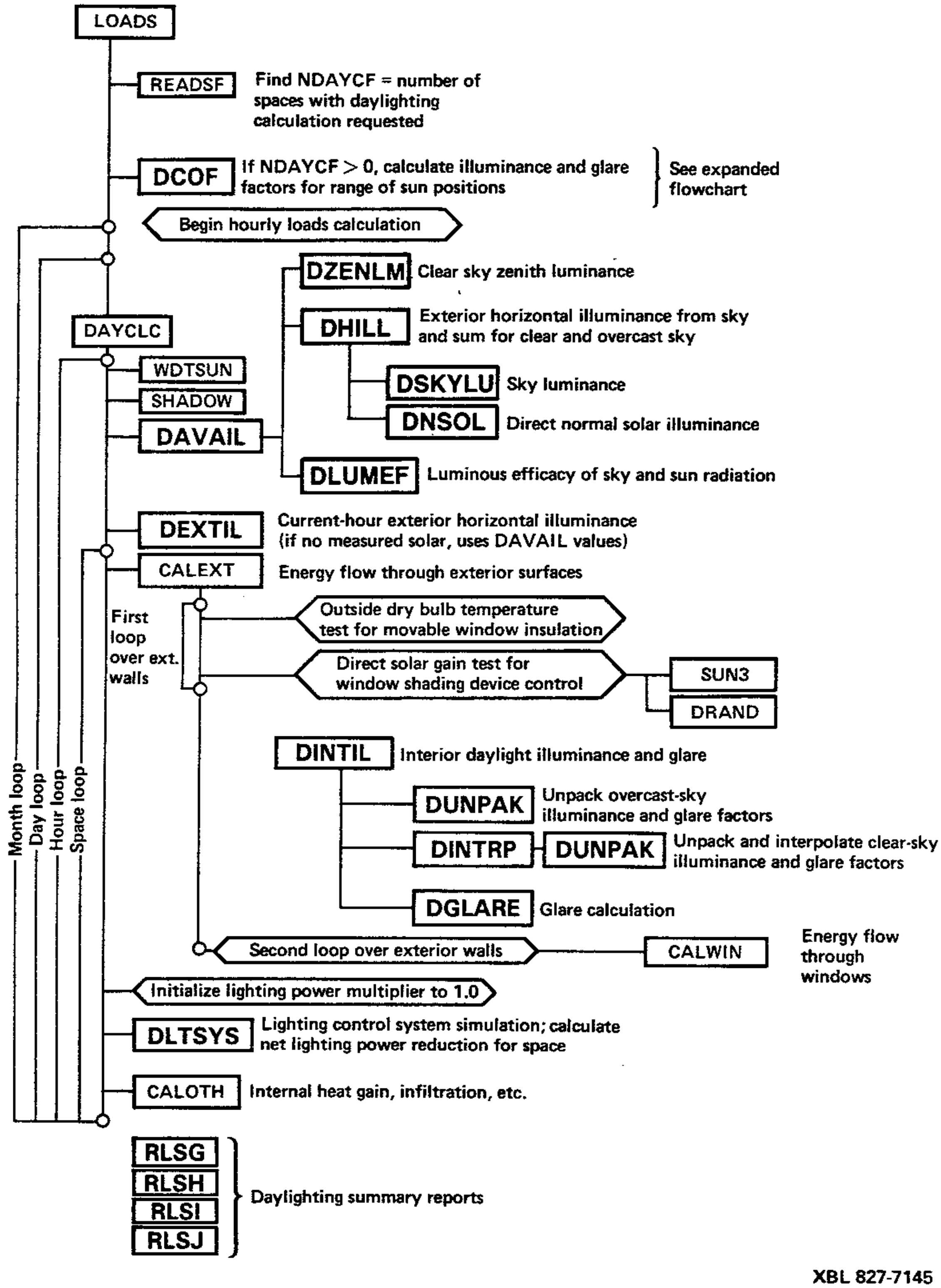


Table 2. DOE-2.1B daylighting calculation flowchart. Daylighting subroutines are in boldface. Some LOADS non-daylighting subroutines are also shown.

calculation and sun control systems such as shades, drapes and blinds that are assumed to be ideal diffusers. The program will be expanded to allow modeling of more geometrically complex sunshading solutions such as horizontal or vertical louvers based upon results calculated in the SUPERLITE program or determined by model measurements. These results would be stored in a library and could be specified by the user. For one-of-a-kind building designs, the user will be allowed to input his/her own daylight coefficients based upon model tests made on that unique design. The final model should be responsive to the latest in architectural design strategies.

2. The Daylighting Preprocessor (Subroutine DCOF)

2.1 Overview

For each daylit space, the preprocessor calculates a set of illuminance and glare factors for later use in the hourly loads calculation. The basic steps are:

1. Calculate exterior horizontal daylight illuminance from sun and sky for standard (CIE) clear and overcast skies for a range of solar altitudes.

2. Calculate interior illuminance and glare for each window/reference-point combination, for bare and for shaded window conditions (if a shading device has been specified), for overcast sky, and for standard clear sky for a series of sun positions covering the annual range of solar altitude and azimuth for the specified building latitude.

3. Divide interior illuminance and glare quantities by exterior horizontal illuminance to obtain daylight factors, which are then packed and stored in the AA array.

2.2 Interior Illuminance Components

In the preprocessor, daylight incident on a window is separated into two components: (1) light which originates from the sky, and reaches the window directly or by reflection from exterior surfaces; and (2) light which originates from the sun, and reaches the window directly or by reflection from exterior surfaces. Light from the window then reaches the workplane directly or via reflection from the interior surfaces of the room.

Fig.1a-e shows schematically the various paths by which diffuse light originating from the sky can pass through a window (without a shading device) and reach a reference point on the workplane:

(a) light from sky passes through window directly and reaches workplane without internal reflection.

(b) as in (a) but light reflects internally before reaching workplane.

(c) light from sky reflects from ground, then enters window and reaches workplane after internal refraction. (Note that light reflected from a horizontal ground plane cannot reach the workplane directly.)

(d) light from sky illuminates an obstruction or is reflected from the ground onto the obstruction. Light reflected from the obstruction passes through the window and reaches workplane without internal reflection.

(e) as in (d), but light reflects internally before reaching workplane.

Fig.1f-i shows similar paths for light originating from the sun.

Fig. 2a-f shows the situation in which the window is covered by a diffusing shade:*

(a) light from sky illuminates shade. Light transmitted by shade reaches workplane directly or by internal reflection.

(b) as in (a) but shade is illuminated by light from sky after reflecting from ground.

(c) light from sky illuminates an obstruction or is reflected from ground onto the obstruction. Light reflected from the obstruction illuminates the shade. Light transmitted by shade reaches workplane directly or by internal reflection.

(d)-(f) as in (a)-(c) above but light originates from sun.

For fixed sun position, sky condition (clear or overcast) and room geometry, the sky-related interior daylight will be proportional to the exterior horizontal illuminance, $E_{h,sky}$, due to light from the sky. Similarly, the sun-related interior daylight will be proportional to the exterior horizontal solar illuminance $E_{h,sun}$.

---

* By "shades" or "window-shades" are meant devices such as drapes, blinds, pull-down shades, etc., which are used on a window for sun or glare control. They are distinguished from "building-shades" (also called "obstructions") such as fins, overhangs, neighboring buildings etc.

Bare window

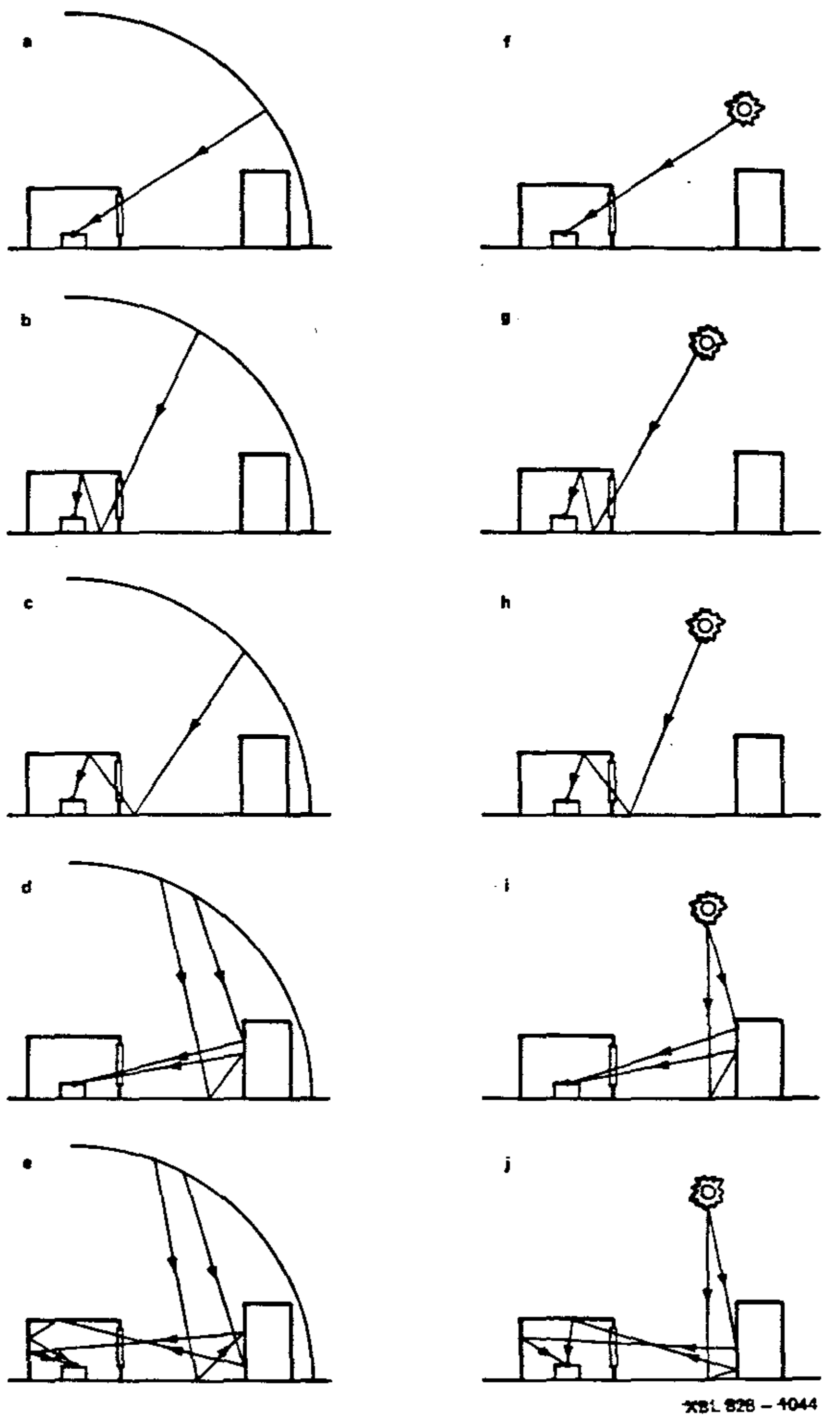


Fig. 1. Paths by which light originating from sky (a–e) and from sun (f–j) can reach workplane through a transparent window without a shading device.

Window with diffusing shade

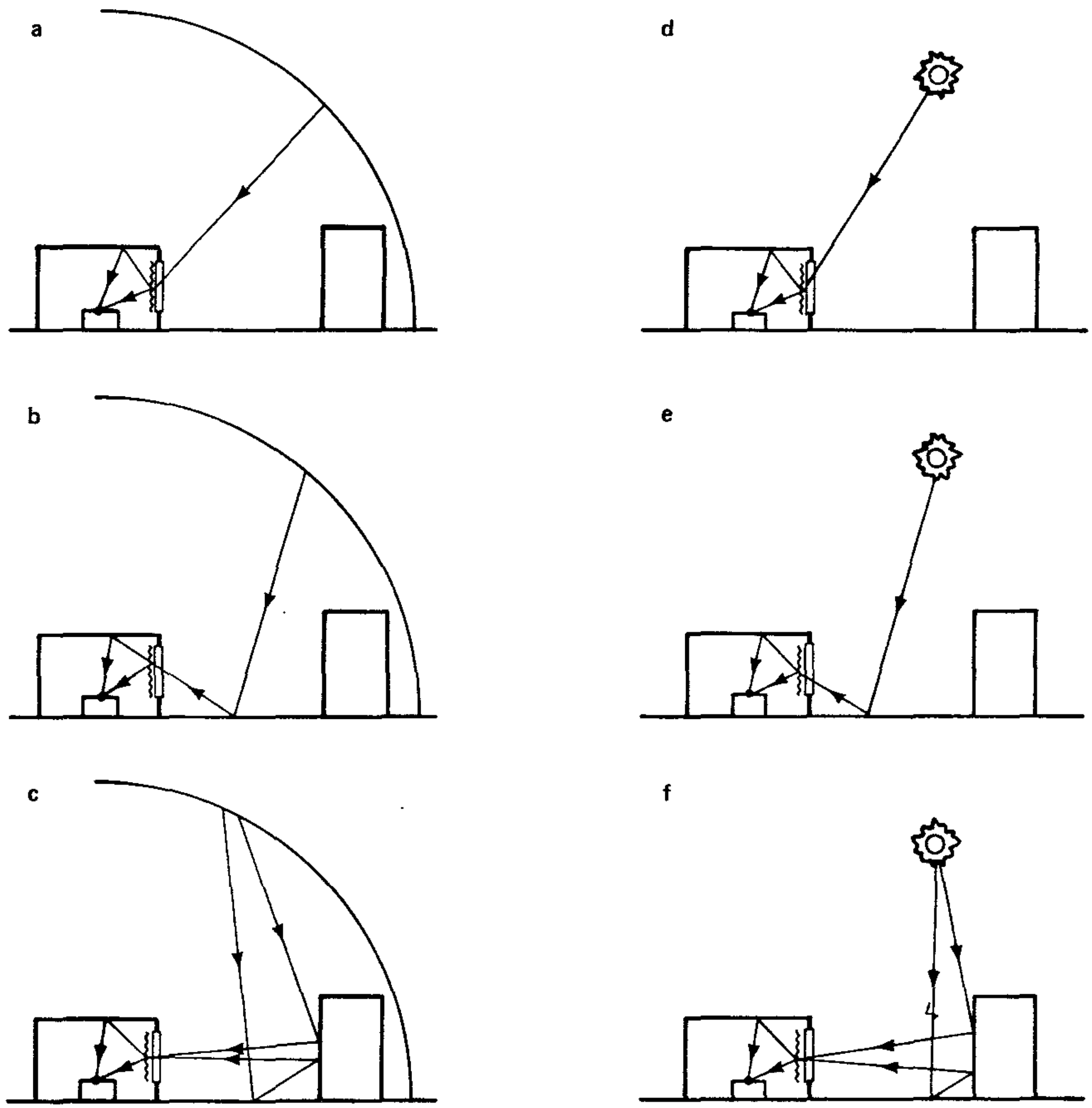


Fig. 2. Paths by which light originating from sky (a-c) and from sun (d-f) can reach workplane through a transparent window with a diffusing shading device.

2.3 Daylight Factors

The following interior/exterior illuminance ratios, called "daylight factors", are calculated and stored for later use in the hourly LOADS calculation:

$$d_{sky} = \frac{\text{illuminance at reference point due to sky-related light}}{E_{h,sky}}$$

$$d_{sun} = \frac{\text{illuminance at reference point due to sun-related light}}{E_{h,sun}}$$

$$w_{sky} = \frac{\text{average window luminance due to sky-related light}}{E_{h,sky}}$$

$$w_{sun} = \frac{\text{average window luminance due to sun-related light}}{E_{h,sun}}$$

$$b_{sky} = \frac{\text{window background luminance due to sky-related light}}{E_{h,sky}}$$

$$b_{sun} = \frac{\text{window background luminance due to sun-related light}}{E_{h,sun}}$$

These factors depend, in general, on:

room conditions:

1. room geometry
2. interior surface reflectances
3. position of reference point
4. window geometry
5. glass transmittance
6. position of window shade (exterior vs interior)
7. transmittance of window shade

external conditions:

8. location of external obstructions (e.g. fins, overhangs, or adjacent buildings)
9. reflectance of external obstructions
10. condition of sky - clear vs overcast
11. position of sun (for clear sky)

For a daylit space with N windows the 6 daylight factors

$$d_{sky},\ d_{sun},\ w_{sky},\ w_{sun},\ b_{sky},\ \text{and}\ b_{sun}$$

are calculated for each of the following combinations of window, reference point, sky condition, sun position, and shading device:

$$\begin{bmatrix}\text{Ref. pt. \#1}\\ \text{(and \#2}\\ \text{if defined)}\end{bmatrix} \begin{bmatrix}\text{Window \#1}\\ \text{Window \#2}\\ \cdot\\ \cdot\\ \cdot\\ \text{Window \#N}\end{bmatrix} \begin{bmatrix}\text{Clear sky,}\\ \text{sun pos. \#1}\\ \cdot\\ \cdot\\ \cdot\\ \text{Clear sky,}\\ \text{sun pos. \#20}\\ \text{Overcast sky,}\\ \text{sun pos. \#1}\end{bmatrix} \begin{bmatrix}\text{Bare window}\\ \text{Window plus shade}\\ \text{(if shade is}\\ \text{specified)}\end{bmatrix}$$

For example, for a room with one window, one reference point, and no window-shade, we have

$$6 \times (1 \times 1 \times 21 \times 1) = 126 \text{ daylight factors}$$

For building latitude λ degrees, the 20 sun positions for the clear sky case are

azimuth (clockwise from north): 70, 125, 180, 235, 290 degrees;

altitude (degrees): $10,\ 10 + \frac{1}{3}(\phi_m - 10),\ 10 + \frac{2}{3}(\phi_m - 10),\ \phi_m$

where ϕ_m, the maximum solar altitude, is min $(113.5^o - \lambda, 90^o)$. Fig. 3 shows the sun positions for $\lambda = 40^o$.

2.4 Sky Luminance Distributions

Clear Sky

The clear sky luminance distribution, which was derived by Kittler from measurements in Europe, has the form (Refs. 2 and 3):

$$L(\theta_{sky},\phi_{sky}) = L_z \frac{(0.91+10e^{-3\gamma}+0.45\cos^2\gamma)(1-e^{-0.32\,\mathrm{cosec}\,\phi_{sky}})}{.27385\ (0.91+10e^{-3(90-\phi_{sun,deg})}+0.45\sin^2\phi_{sun})} \tag{1}$$

where

ϕ_{sky} = altitude of sky element,
θ_{sky} = azimuth of sky element,

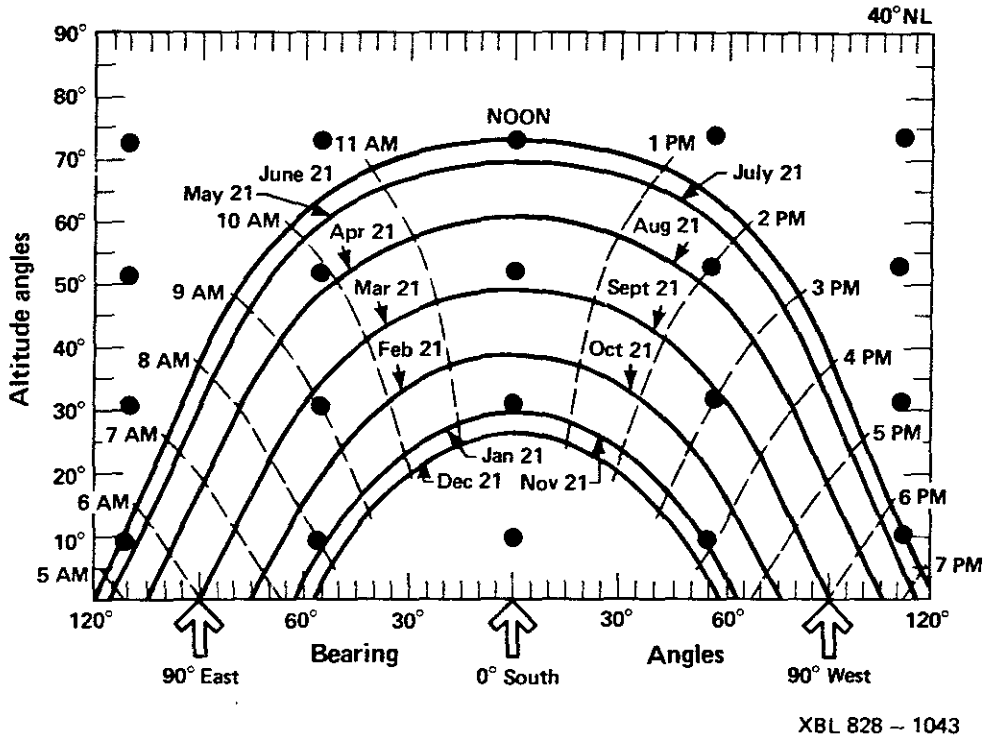


Fig. 3. Sun positions (•) for calculation of clear sky daylight factors for 40° north latitude. (Sunchart reproduced from "The Passive Solar Energy Book", Edward Mazria, Rodale Press, Emmaus, PA, 1979.)

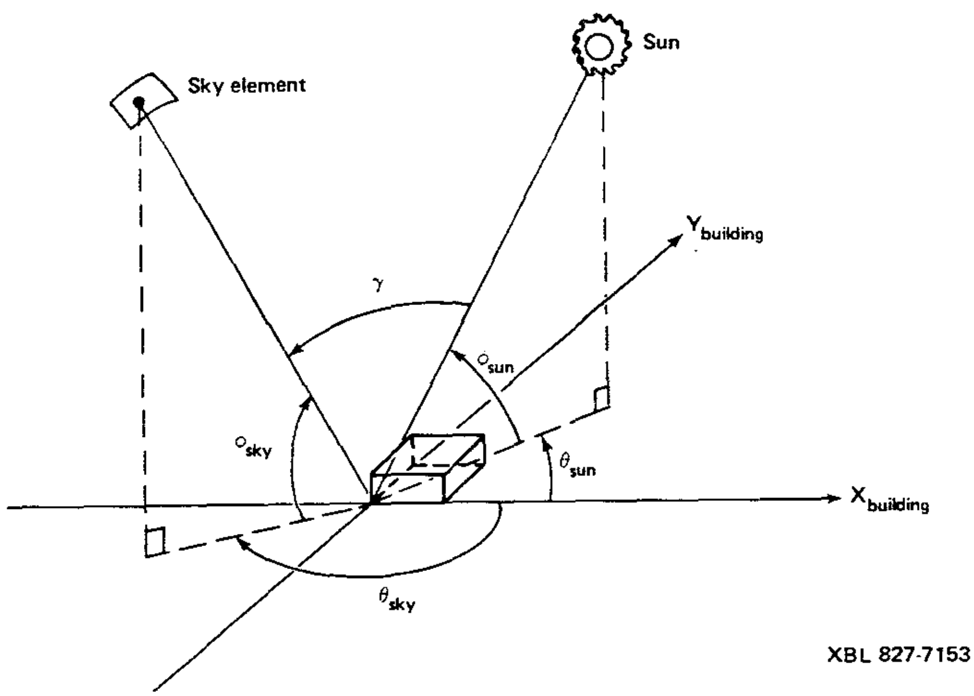
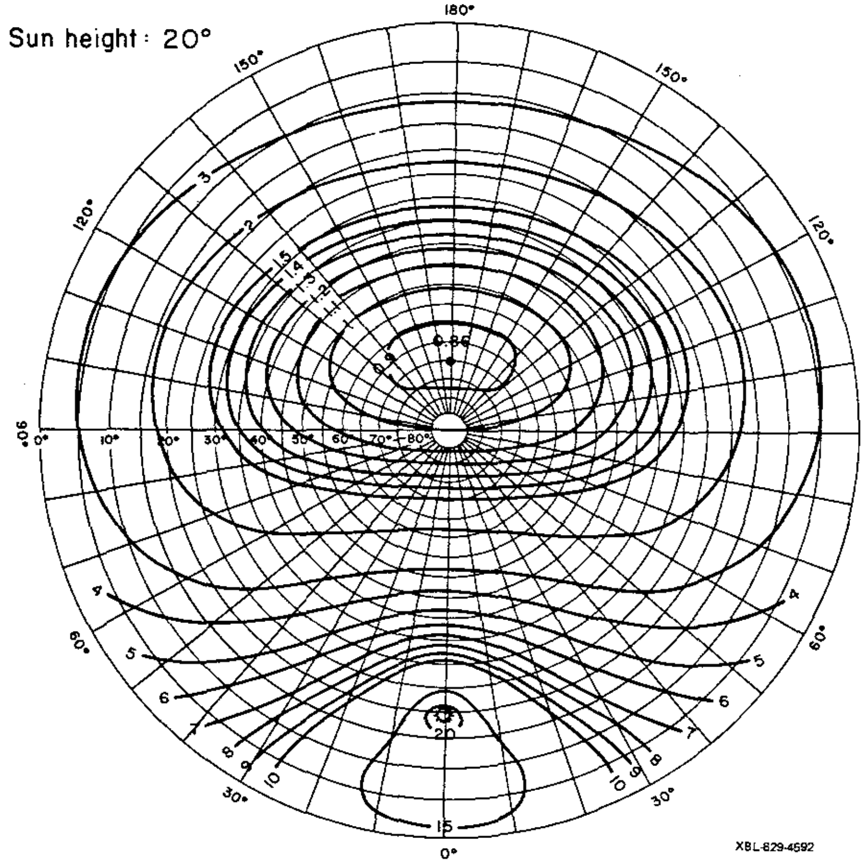


Fig. 4. Angles used in clear sky luminance distribution.



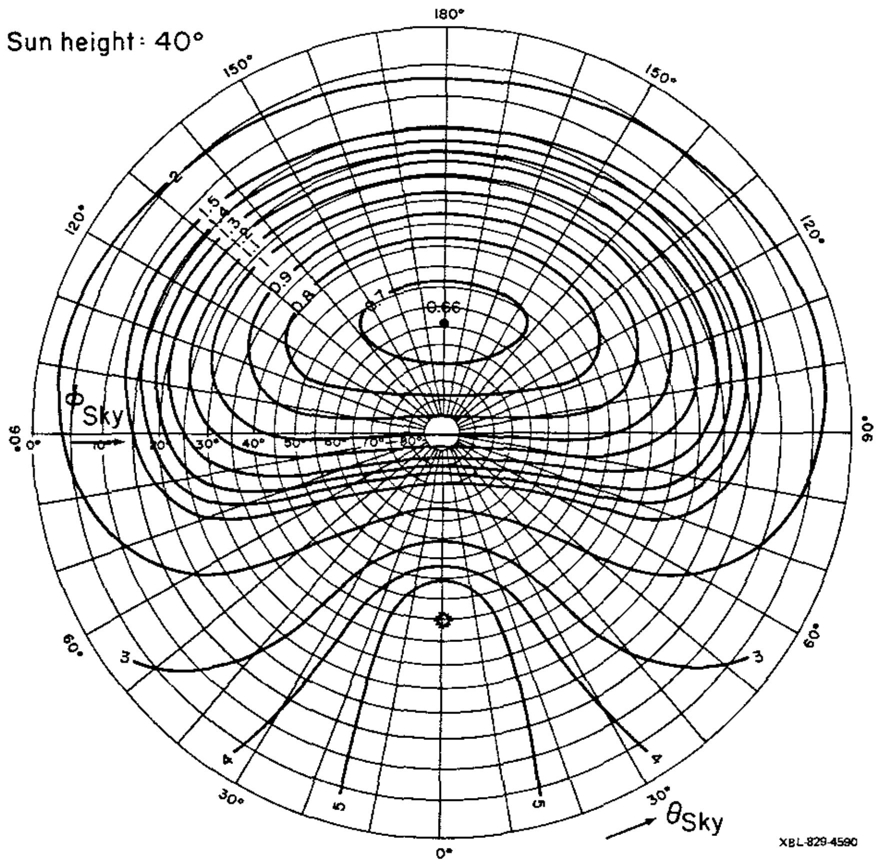
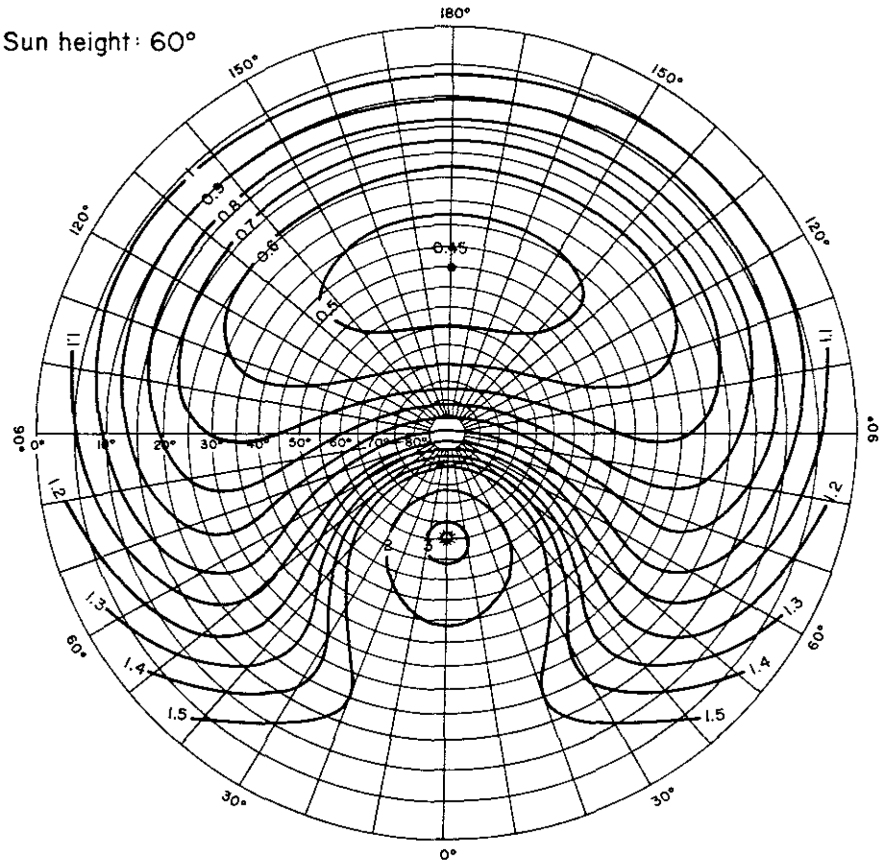


Fig. 5. Clear sky luminance distributions (normalized to unit zenith luminance) for different solar altitudes [Ref. 3].

Sun height: 60°



Sun height: 80°

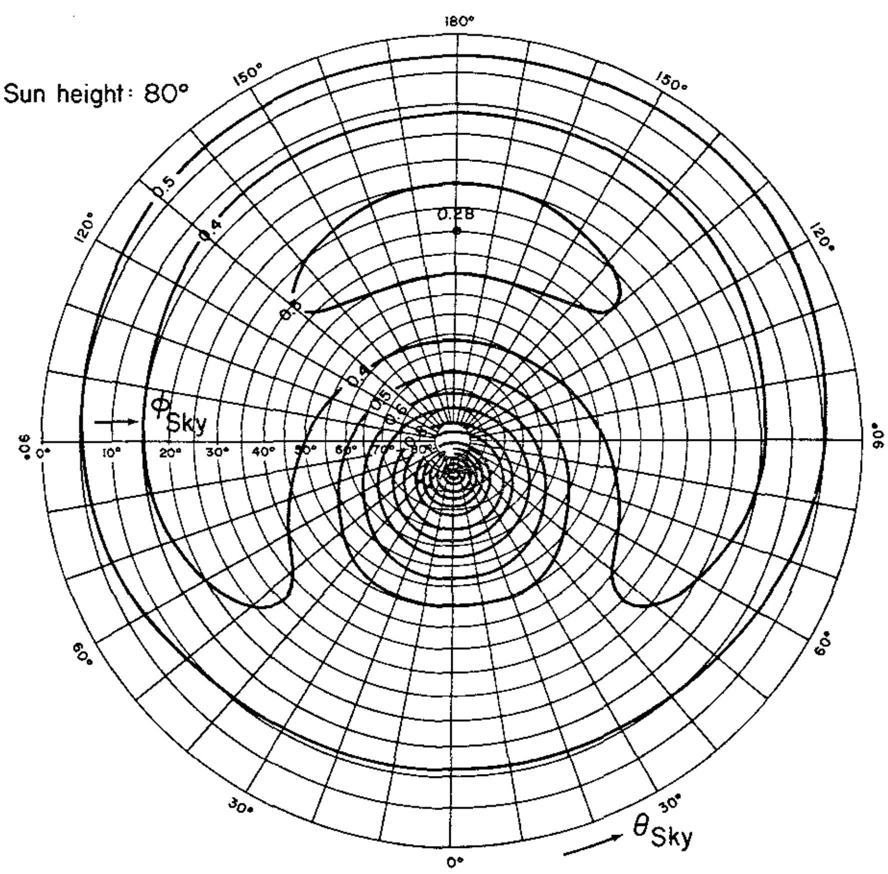


Fig. 5. (Cont.)

ϕ_{sun} = altitude of sun,
$\phi_{sun,deg}$ = altitude of sun in degrees,
L_z = luminance of sky at zenith,
γ = angle between sun and sky element.

The various angles, which are defined in the building coordinate system, are shown in Fig. 4. The angle γ between sun and sky element is given by

$$\gamma = \cos^{-1}[\sin\phi_{sky}\sin\phi_{sun}+\cos\phi_{sky}\cos\phi_{sun}\cos(\theta_{sky}-\theta_{sun})] \quad (2)$$

Contour plots of $L(\theta_{sky}, \phi_{sky})/L_z$ are shown in Fig. 5 for solar altitude angles of 20°, 40°, 60°, and 80° (reproduced from Ref. 3). A three-dimensional plot of $L(\theta_{sky}, \phi_{sky})/L_z$ as measured by Liebelt (Ref. 4) for ϕ_{sun}=27° is shown in Fig. 6. From these figures, the general characteristics of the distribution are seen to be a large peak near the sun; a minimum at a point on the other side of the zenith from the sun, in the vertical plane containing the sun; and an increase in luminance as the horizon is approached.

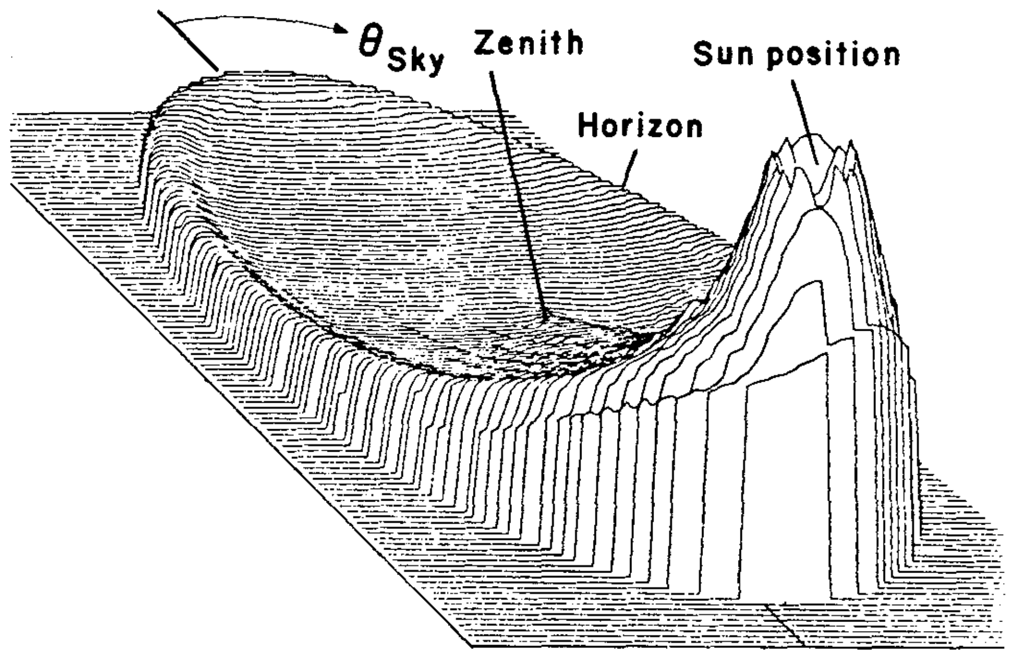


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Fig. 6. Clear sky luminance distribution as measured by Liebelt [Ref. 4] for a solar altitude of 27°.

The zenith luminance in Eq. 1 is given by

$$L_z[\mathrm{kcd/m^2}] = (1.34T-3.46)\tan\phi_{sun}+0.10T+0.90, \quad \phi_{sun} \le 60^\circ \quad (3)$$

where T is Linke's turbidity factor. This equation was was derived by Liebelt (Ref. 4) from measurements made in Germany at 49° North Latitude.

For $\phi_{sun}>60^o$, where Eq. 3 is invalid, L_z is found by constraining the horizontal illuminance, E_{hcl}, to increase as $\sin\phi_{sun}$, i.e.

$$E_{hcl}\ (\phi_{sun} \geq 60^o) = \frac{E_{hcl}\ (60^o)\ \sin\phi_{sun}}{\sin 60^o}$$

The correlation between L_z and E_{hcl} is found by integrating Eq. 1 over the skydome to obtain E_{hcl}:

$$\begin{aligned} E_{hcl}(\phi_{sun},T) &= \int L(\theta_{sky},\phi_{sky})\ \sin\phi_{sky}\ d\Omega_{sky} \\ &= L_z\ (\phi_{sun},T)\ A(\phi_{sun})\ , \end{aligned}$$

where $A(\phi_{sun})$ is the integral over the right-hand side of Eq. 1 excluding the L_z factor. We have then

$$\begin{aligned} L_z(\phi_{sun},T) &= \frac{E_{hcl}(\phi_{sun},T)}{A(\phi_{sun})} \\ &= \frac{L_z(60^o,T)\ A(60^o)\ \sin\phi_{sun}}{A(\phi_{sun})\sin 60^o}\quad \phi_{sun} \geq 60^o \end{aligned}$$

Fig. 13 of Ref. 19 shows that A decreases almost quadratically above 60°. It can be approximated to a few percent by

$$A(\phi_{sun}) = 3.25 - .1050(\phi_{sun}-60) + .0010(\phi_{sun}-60)^2,$$

$$\phi_{sun} \geq 60^o.$$

Thus,

$$L_z(\phi_{sun},T) = \frac{3.25L_z(60^o)\sin\phi_{sun}}{[3.25-.1050(\phi_{sun}-60)+.0010(\phi_{sun}-60)^2]\sin 60^o},$$

$$\phi_{sun} \geq 60^o. \tag{4}$$

The turbidity factor, T, relates the direct normal solar illuminance at the earth's surface, E_{DN}, to the extraterrestrial direct normal illuminance, E^o_{DN}, according to

$$E_{DN} = E^o_{DN}\ e^{-\bar{a}_R mT} \tag{5}$$

where

$\bar{a}_R$ = atmospheric extinction coefficient due to Rayleigh scattering
m = optical air mass of atmosphere.

T is a measure of the aerosol and moisture content of the atmosphere. It has been empirically determined by Dogniaux (Refs. 5 and 6) to have the form

$$T = \left[\frac{\phi_{sun,deg} + 85}{39.5\ e^{-w} + 47.4} + 0.1 \right] + (16 + 0.22w)\ \beta \tag{6}$$

where

w = amount of precipitable moisture in the atmosphere [cm]
β = Angstrom's turbidity coefficient.

The value of T ranges from about 2 for a very clean, dry atmosphere, to 5 and above for moist, polluted conditions. w and β vary with time and with geographical location. In DOE-2, monthly average values of w and β are entered. Tables 3 and 4 list monthly average values of w and β for different locations in the United States (Refs. 7, 8, and 9). As described in Refs. 6 and 8, w is determined by integrating radiosonde measurements of moisture content at different altitudes, and β is found from sunphotometer measurements by comparing, at specific wavelengths, direct normal solar irradiance at the earth's surface with the corresponding extraterrestrial irradiance, taking into account the optical air mass.

Table 3

Monthly Average Atmospheric Moisture (inches of water) for U.S. Cities

City	Month											
	J	F	M	A	M	J	J	A	S	O	N	D
Montgomery, AL	.65	.56	.65	.85	1.00	1.31	1.58	1.60	1.39	.95	.67	.69
Ft. Smith, AR	.48	.47	.56	.78	1.08	1.39	1.66	1.56	1.16	1.03	.53	.48
Little Rock, AR	.51	.46	.55	.81	.94	1.26	1.47	1.42	1.29	.86	.63	.59
Ft. Huachuca, AZ	.27	.27	.24	.26	.36	.59	1.01	1.01	.73	.48	.31	.27
Phoeniz, AZ	.42	.38	.38	.45	.51	.67	1.29	1.31	.92	.63	.43	.40
China Lake, CA	.28	.25	.28	.34	.38	.40	.66	.68	.47	.33	.29	.32
Point Mugu, CA	.46	.45	.48	.51	.65	.79	1.04	.97	.89	.69	.54	.49
San Diego, CA	.46	.46	.47	.50	.60	.71	.98	1.04	.83	.62	.60	.48
San Nicolas Is., CA	.47	.42	.43	.42	.52	.65	.85	.80	.73	.61	.53	.46
Santa Maria, CA	.48	.48	.48	.52	.61	.68	.82	.80	.74	.63	.55	.49
Santa Monica, CA	.48	.51	.49	.56	.65	.75	.93	.95	.85	.72	.54	.50
Oakland, CA	.52	.49	.48	.45	.53	.63	.64	.67	.64	.59	.61	.50
Denver, CO	.20	.19	.21	.27	.41	.57	.75	.71	.51	.35	.25	.20
Grand Junction, CO	.25	.24	.24	.28	.39	.51	.73	.72	.52	.41	.31	.26
Key West, FL	1.04	1.03	1.06	1.13	1.34	1.65	1.64	1.71	1.78	1.53	1.20	1.05
Cocoa Beach, FL	.86	.85	.95	1.03	1.26	1.60	1.73	1.79	1.76	1.37	1.02	.90
Miami, FL	.96	.95	1.00	1.10	1.31	1.64	1.69	1.74	1.77	1.50	1.16	1.10
Atlanta, GA	.54	.52	.56	.72	.95	1.26	1.48	1.45	1.20	.83	.59	.54
Boise, ID	.35	.32	.30	.34	.44	.59	.60	.60	.52	.42	.40	.32
Peoria, IL	.30	.31	.37	.55	.76	1.02	1.17	1.13	.96	.65	.46	.36
Salem, IL	.31	.35	.41	.57	.72	1.09	1.19	1.19	1.12	.74	.46	.42
Joliet, IL	.36	.32	.40	.53	.76	1.11	1.21	1.12	.88	.66	.43	.35
Dodge City, KS	.28	.27	.30	.42	.61	.86	1.09	1.04	.81	.53	.37	.30
Lake Charles, LA	.74	.72	.77	.95	1.17	1.45	1.70	1.67	1.50	1.05	.83	.78
Boothville, LA	.82	.72	.78	1.00	1.13	1.41	1.69	1.72	1.60	1.17	.87	.94
Nantucket, MA	.38	.36	.40	.53	.73	.97	1.15	1.26	.95	.71	.56	.42
Caribou, ME	.23	.22	.26	.36	.55	.79	.95	.90	.74	.55	.40	.27
Portland, ME	.30	.29	.33	.46	.66	.93	1.08	1.05	.87	.63	.49	.34
Sault Ste. Marie, MI	.23	.22	.27	.39	.57	.83	.92	.93	.78	.58	.39	.28
Flint, MI	.27	.26	.31	.46	.64	.89	.99	.97	.86	.61	.43	.33
Int'l Falls, MN	.19	.19	.23	.35	.52	.77	.90	.87	.68	.49	.30	.22
St. Cloud, MN	.22	.23	.27	.42	.63	.86	1.00	.99	.77	.56	.34	.26
Columbia, MO	.36	.32	.42	.62	.78	1.10	1.23	1.21	.98	.70	.52	.42
Jackson, MS	.59	.60	.65	.87	1.05	1.36	1.59	1.56	1.36	.92	.71	.65
Great Falls, MT	.23	.22	.23	.27	.39	.54	.58	.58	.46	.34	.28	.23
Glasgow, MT	.23	.24	.25	.34	.49	.68	.77	.73	.57	.42	.31	.25
North Platte, NB	.26	.28	.30	.41	.62	.85	1.02	.99	.72	.49	.33	.28
Omaha, NB	.28	.29	.35	.50	.74	1.03	1.18	1.13	.87	.62	.40	.31
Greensboro, NC	.47	.45	.50	.65	.90	1.18	1.39	1.37	1.11	.77	.55	.47
Cape Hatteras, NC	.59	.52	.56	.70	.96	1.20	1.57	1.57	1.25	.97	.67	.63
Bismarck, ND	.22	.24	.26	.38	.56	.81	.93	.88	.65	.47	.31	.25
Rapid City, ND	.26	.26	.28	.37	.53	.75	.87	.81	.59	.42	.30	.26
Ely, NE	.21	.20	.20	.22	.31	.42	.54	.57	.38	.29	.26	.21
Albuquerque, NM	.21	.20	.21	.24	.33	.47	.80	.79	.58	.38	.27	.22
Albany, NY	.30	.28	.35	.48	.70	.98	1.11	1.10	.93	.65	.49	.36
Buffalo, NY	.30	.29	.34	.47	.66	.91	1.04	1.02	.87	.63	.46	.35

New York City, NY	.34	.33	.40	.54	.76	1.02	1.18	1.16	1.01	.69	.55	.42
Dayton, OH	.33	.33	.39	.56	.74	1.00	1.13	1.08	.93	.65	.47	.38
Medford, OR	.46	.42	.40	.41	.51	.65	.67	.67	.59	.52	.53	.43
Salem, OR	.52	.48	.45	.47	.56	.71	.73	.76	.70	.62	.60	.51
Pittsburgh, PA	.34	.32	.38	.52	.72	.97	1.09	1.06	.90	.63	.47	.37
Charleston, SC	.65	.63	.68	.83	1.11	1.42	1.67	1.66	1.43	1.02	.75	.66
Nashville, TN	.45	.41	.49	.70	.85	1.13	1.33	1.31	1.19	.77	.55	.53
Amarillo, TX	.28	.26	.30	.39	.55	.80	1.03	1.00	.80	.52	.37	.30
El Paso, TX	.29	.28	.30	.33	.44	.67	.98	1.00	.83	.52	.37	.32
Midland, TX	.34	.33	.37	.48	.65	.89	1.06	1.10	.97	.64	.44	.36
Ft. Worth, TX	.48	.51	.58	.80	1.06	1.32	1.48	1.46	1.28	.90	.65	.54
Del Rio, TX	.53	.55	.59	.85	1.09	1.33	1.39	1.43	1.37	1.01	.70	.55
Brownsville, TX	.90	.90	.94	1.12	1.31	1.48	1.57	1.60	1.64	1.31	1.07	.96
Salt Lake City, UT	.29	.26	.25	.30	.40	.54	.66	.66	.50	.38	.34	.27
Quillayute – Tatoosh Is., WA	.46	.47	.44	.48	.57	.71	.77	.82	.75	.67	.55	.50
Green Bay, WI	.23	.23	.28	.44	.63	.89	1.02	.99	.82	.60	.39	.28
Huntington, WV	.39	.37	.47	.62	.82	1.08	1.25	1.19	1.04	.72	.53	.45
Lander, WY	.18	.17	.18	.24	.33	.47	.54	.53	.40	.29	.23	.18

Source: George A. Lott, "Precipitable Water Over the United States, Volume 1: Monthly Means", National Oceanic and Atmospheric administration Technical Report NWS 20, November 1976.

Table 4

Monthly Average Atmospheric Turbidity for U. S. Cities

City	Source	J	F	M	A	M	J	J	A	S	O	N	D
Eielson AB, AL	2	.03	.03	.11	.11	.20	.07	.09	.12	.07	.04	.04	.04
Little Rock, AR	2	.11	.16	.17	.22	.22	.20	.22	.20	.19	.13	.10	.09
Tucson, AZ	1	.05	.05	.06	.07	.07	.07	.07	.07	.07	.06	.06	.07
Los Angeles, CA	1	.11	.14	.15	.16	.18	.21	.20	.21	.19	.17	.11	.11
Edwards AFB, CA	2	.02	.02	.06	.09	.09	.08	.08	.08	.07	.06	.04	.04
Boulder, CO	1	.04	.05	.07	.09	.08	.07	.07	.07	.07	.05	.05	.04
Alamosa, CO	2	.09	.11	.12	.15	.13	.10	.10	.06	.07	.07	.07	.07
Washington, DC	1	.11	.12	.15	.17	.19	.21	.24	.20	.17	.13	.13	.13
Tallahassee, FL	2	.12	.18	.19	.20	.28	.34	.35	.25	.25	.19	.18	.12
Miami, FL	2	.19	.29	.30	.31	.36	.54	.51	.55	.40	.33	.31	.24
Idaho Falls, ID	1	.03	.04	.06	.07	.07	.07	.06	.06	.06	.05	.04	.03
Chicago, IL	1	.15	.18	.21	.18	.18	.19	.22	.16	.16	.14	.13	.15
Salem, IL	2	.09	.10	.16	.17	.21	.22	.23	.21	.17	.16	.10	.09
Topeka, KS	1	.05	.07	.07	.07	.09	.12	.09	.07	.07	.06	.04	.04
Blue Hill, MA	1	.07	.07	.09	.11	.13	.16	.17	.13	.08	.07	.07	.06
Baltimore, MD	1	.12	.18	.18	.19	.22	.27	.31	.32	.31	.12	.17	.18
College Park, MD	2	.07	.08	.13	.17	.23	.21	.13	.23	.17	.13	.08	.07
St. Cloude, MN	2	.08	.06	.08	.13	.11	.09	.11	.10	.08	.06	.05	.05
St. Louis, MO	1	.12	.12	.16	.17	.21	.20	.22	.19	.19	.12	.12	.11
Meridian, MS	1	.07	.07	.07	.09	.12	.15	.15	.13	.11	.07	.07	.07
Missoula, MT	1	.06	.07	.07	.08	.09	.07	.07	.06	.09	.08	.07	.07
Greensboro, NC	1	.07	.08	.09	.11	.14	.24	.22	.21	.14	.08	.07	.07
Raleigh, NC	2	.06	.10	.10	.10	.12	.14	.24	.15	.13	.06	.06	.04
Bismarck, ND	2	.04	.02	.04	.08	.08	.07	.05	.06	.07	.08	.08	.05
Brookhaven, NY	1	.07	.07	.10	.11	.12	.14	.15	.11	.12	.07	.07	.07
Albany, NY	1	.10	.09	.11	.12	.14	.14	.15	.15	.14	.11	.10	.09
New York City, NY	1	.11	.11	.12	.15	.17	.22	.21	.24	.20	.15	.11	.11
Cincinnati, OH	1	.07	.09	.12	.13	.14	.20	.20	.19	.17	.12	.10	.08
Toledo, OH	2	.09	.08	.12	.11	.15	.13	.15	.11	.09	.05	.06	.06
Youngstown, OH	2	.14	.14	.16	.19	.25	.29	.22	.28	.22	.17	.15	.13
Pendleton, OR	2	.10	.12	.16	.20	.19	.19	.16	.15	.11	.09	.09	.09
Philadelphia, PA	1	.12	.15	.18	.20	.22	.25	.27	.23	.17	.15	.14	.14
Huron, SD	1	.04	.05	.07	.07	.08	.09	.08	.07	.07	.06	.05	.04
Memphis, TN	1	.08	.08	.10	.16	.15	.18	.19	.16	.16	.09	.10	.08
Oak Ridge, TN	2	.10	.14	.13	.17	.33	.26	.37	.31	.25	.13	.09	.09
College Stn., TX	1	.10	.10	.11	.12	.13	.08	.15	.12	.11	.09	.08	.07
Victoria, TX	2	.03	.03	.05	.02	.08	.08	.06	.05	.04	.04	.03	.02
Grand Prarie, TX	2	.07	.12	.16	.16	.36	.35	.36	.53	.45	.23	.19	.21
Green Bay, WI	2	.09	.09	.15	.16	.19	.17	.16	.10	.09	.10	.05	.06
Elkins, WV	1	.07	.07	.09	.14	.15	.21	.21	.19	.14	.07	.07	.07

Source: 1. E. C. Flowers, R. A. McCormick, and K. R. Kurfis, "Atmospheric Turbidity over the United States, 1961-66", Journal of Applied Meteorology, Vol. 8, No. 6, 1969, pp. 955-962.

2. "Global Monitoring of the Environment for Selected Atmospheric Constituents, 1977", Environmental Data and Information Service, National Climatic Center, Asheville, NC, June 1980.

Note: This table contains values for the Angstrom turbidity coefficient (β).

Overcast Sky

The standard overcast sky luminance distribution, which was originally derived by Moon and Spencer (Ref. 10) from empirical data, has the form

$$L_{oc}\ (\phi_{sky}) = L_{z,oc} \frac{1+2\ \sin\ \phi_{sky}}{3}\ , \qquad (7)$$

where $L_{z,oc}$, the zenith luminance derived by Krochmann (Ref. 11), is

$$L_{z,oc}\ [\mathrm{kcd/m^2}] = 0.123 + 8.6\ \sin\phi_{sun} \qquad (8)$$

This is plotted in Fig. 7.

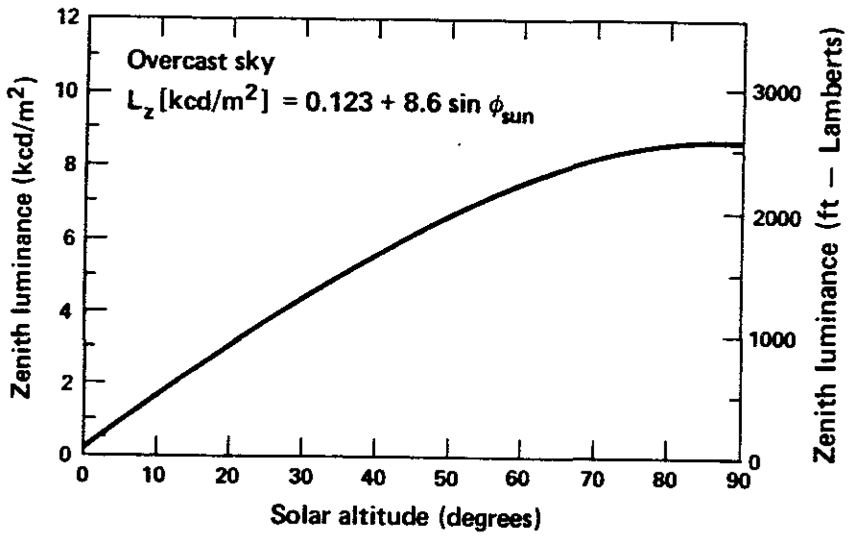

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Fig. 7. Overcast sky zenith luminance, L_z, according to Krochmann [Ref. 11].

From Eq. 7 we note that the overcast sky luminance distribution, unlike the clear sky case, does not depend on either the solar azimuth or the sky azimuth. We also note that, at fixed solar altitude, the zenith ($\phi_{sky} = \pi/2$) is three times brighter than the horizon ($\phi_{sky} = 0$).

2.5 Direct Normal Solar Illuminance, Clear Sky

The direct normal solar illuminance at the earth's surface under clear sky conditions is determined from Eq. 5. From Dogniaux (Ref.5) we have the following parameterizations for E^o_{DN}, $\bar{a}_R$ and m:

$$\begin{aligned} E^o_{DN}\ [\mathrm{klx}] = {} & 126.82 + 4.248 \cos \omega J + 0.08250 \cos 2\omega J \\ & - 0.00043 \cos 3\omega J + 0.1691 \sin \omega J \\ & + 0.00914 \sin 2 \omega J + 0.01726 \sin \omega J \end{aligned} \qquad (9)$$

where J is the number of the day of the year ($1 \leq J \leq 366$) and $\omega = 2\pi/366$. The dependence on J accounts for the variation of the solar constant with changing earth-sun distance.

$$\begin{aligned} \bar{a}_R &= 0.1512 - 0.0262T \text{ for } \beta < 0.075, \\ &= 0.1656 - 0.0215T \text{ for } 0.075 \leq \beta < 0.15, \\ &= 0.2021 - 0.0193T \text{ for } \beta \geq 0.20. \end{aligned} \tag{10}$$

$$m = (1-0.1h)/[\sin\phi_{sun} + 0.15(\phi_{sun} + 3.885)^{-1.253}] , \tag{11}$$

where h is the building altitude in km.

2.6 Exterior Horizontal Illuminance

The illuminance, E_h, on an unobstructed horizontal plane due to diffuse radiation from the sky is calculated for clear sky and for overcast sky by integrating over the appropriate sky luminance distribution, L:

$$E_h = \int L\ (\theta_{sky}, \phi_{sky})\ \sin\phi_{sky}\ d\Omega_{sky} \tag{12}$$

$$= \int_0^{2\pi} \int_0^{\pi/2} L\ (\theta_{sky}, \phi_{sky})\ \sin\phi_{sky}\ \cos\phi_{sky}\ d\theta_{sky}\ d\phi_{sky}\ ,$$

where L is in cd/ft^2 ($1\ cd/ft^2 = \pi$ ft-Lamberts) and E_h is in lm/ft^2 (foot-candles). For the overcast-sky luminance distribution, Eq. 7, the integration in Eq. 12 can be done in closed form, yielding

$$E_{hoc}\ [\text{footcandles}] = \frac{7\pi}{9} L_{z,oc}\ [cd/ft^2] \tag{13}$$

Using Eq. 7 converted to cd/ft^2 ($1\ kcd/m^2 = 92.94\ cd/ft^2$), we have

$$L_{z,oc}\ [cd/ft^2] = 11.4 + 799.3 \sin\phi_{sun} \quad \text{which gives}$$

$$E_{hoc}\ [\text{footcandles}] = 28 + 1953 \sin\phi_{sun} \tag{14}$$

This is plotted in Fig. 8.

For the clear sky luminance distribution, Eq. 1, the integral in Eq. 12 is replaced by a double summation:

$$E_{hcl} = \sum_{i=1}^{N_\theta} \sum_{j=1}^{N_\phi} L(\theta_{sky}(i), \phi_{sky}(j))\ \sin\phi_{sky}(j) \cos\phi_{sky}(j) \Delta\theta_{sky}\ \Delta\phi_{sky} \tag{15}$$

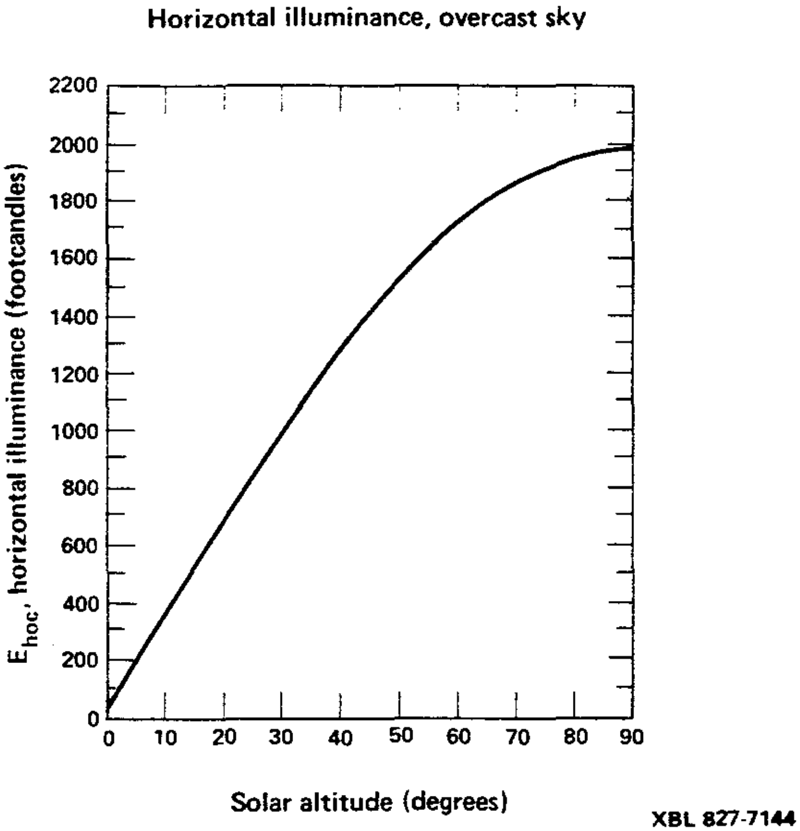

Fig. 8. Exterior horizontal illuminance from CIE overcast sky.

where

$$\theta_{sky}(i) = (i-\tfrac{1}{2})\Delta\theta_{sky},$$

$$\phi_{sky}(j) = (j-\tfrac{1}{2})\Delta\phi_{sky},$$

$$\Delta\theta_{sky} = \frac{2\pi}{N_\theta},$$

$$\Delta\phi_{sky} = \frac{\pi}{2N_\phi}.$$

$N_\theta = 9$ and $N_\phi = 4$ were found to give a ±5% accuracy in the calculation of E_{hcl}.

2.7 Direct Component of Interior Daylight Illuminance

The direct daylight illuminance at a reference point from a particular window is determined by dividing the window into an x-y grid and finding the flux reaching the reference point from each grid element. The geometry involved is shown in Fig. 9. The horizontal illuminance at the reference point, $\overline{R}_{ref}$, due to a window element is

$$dE_h \text{ [footcandles]} = L_w \text{ [cd/ft}^2\text{]} d\Omega \cos\gamma, \tag{16}$$

where

L_w = luminance of window element as seen from reference point,
$d\Omega$ = solid angle subtended by window element with respect to reference point,
γ = angle between vertical and ray from reference point to center of window element.

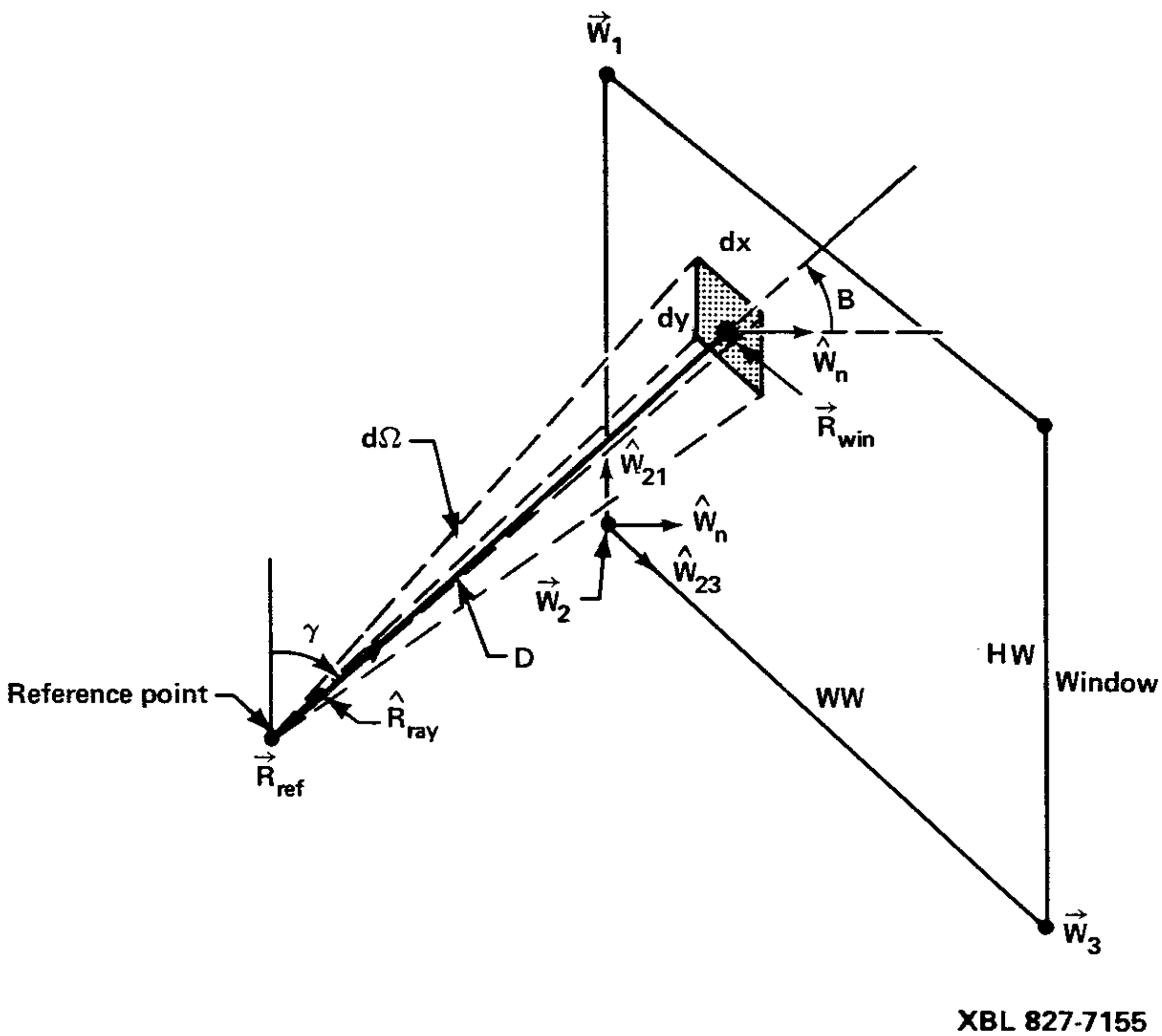

Fig. 9. Geometry for calculation of direct component of daylight illuminance at a reference point. Vectors $\overline{R}_{ref}$, $\overline{W}_1$, $\overline{W}_2$, $\overline{W}_3$, and $\overline{R}_{win}$ are in the building coordinate system.

The subtended solid angle is approximated by

$$d\Omega = \frac{dx\ dy}{D^2} \cos B \tag{17}$$

where

$$D = \left| \overline{R}_{win} - \overline{R}_{ref} \right|$$

dx = width of window element
dy = height of window element
B = angle between window outward normal and ray

cos B is found from

$$\cos B = \overline{R}_{ray} \cdot \overline{W}_n,$$

where

$$\overline{R}_{ray} = (\overline{R}_{win} - \overline{R}_{ref}) / \left| \overline{R}_{win} - \overline{R}_{ref} \right|$$

$\overline{W}_n$ = window outward normal

$$= \overline{W}_{21} \times \overline{W}_{23}$$

$$= \frac{(\overline{W}_1 - \overline{W}_2)}{\left| \overline{W}_3 - \overline{W}_2 \right|} \times \frac{(\overline{W}_3 - \overline{W}_2)}{\left| \overline{W}_3 - W_2 \right|}.$$

Eq. 17 becomes exact as $\frac{dx}{D}$, $\frac{dy}{D} \rightarrow 0$, and is accurate to better than ~1% for dx $\leq$ D/4, dy $\leq$ D/4.

The net illuminance from the window is obtained by summing the contributions from all the window elements:

$$E_h = \sum_{\substack{\text{window}\\ \text{elements}}} L_w \, d\Omega \, \cos\gamma \tag{18}$$

In performing the summation, window elements which lie below the workplane (cos γ < 1) are omitted since light from these elements cannot reach the workplane directly.

Bare window

For the bare window case, the luminance L_w of the window element is found by projecting the ray from reference point to window element and determining whether it intersects the sky, the ground, or an exterior obstruction (local or global building shade). It is assumed that there are no internal obstructions. If L is the corresponding luminance of sky, ground, or exterior obstruction, the window luminance is

$$L_w = L\tau_{vis}(\cos B) ,$$

where τ_{vis} is the visible transmittance of the glass for incidence angle B. This transmittance is calculated from

$$\tau_{vis}(\cos B) = \frac{\tau_{vis}(\cos B=1)}{\tau_{sol}(\cos B=1)} \tau_{sol}(\cos B) , \tag{19}$$

where τ_{sol} is the glass transmittance for the total solar spectrum. This assumes that the visible transmittance has the same angular dependence as the total solar transmittance.

Window with Shade

For the window-plus-shade case, the shade is assumed to be a perfect diffuser, i.e., the luminance of the shade is independent of angle of emission of light, position on shade, and angle of incidence of exterior light falling on the shade. Closely-woven drapery fabric and translucent shades are closer to being perfect diffusers than Venetian blinds and other slatted devices, which tend to have non-uniform luminance characteristics.

The calculation of the shade luminance, L_{sh}, is described in Section 2.10 (see, in particular, Eq. 34). The illuminance contribution at the reference point from a shade element is then given by Eq. 16 with $L_w=L_{sh}$ if shade is inside the window, or $L_w=L_{sh}\ \tau_{vis}(\cos B)$ if shade is outside the window. It should be noted that at this point in the calculation the shade transmittance is taken to be 1.0. The actual shade transmittance, which can be scheduled, is accounted for in the hourly LOADS calculation.

2.8 Internally Reflected Component of Interior Daylight Illuminance

Daylight reaching a reference point after reflection from interior surfaces is calculated using the "split-flux" method (Refs. 12 and 13). In this method, the daylight transmitted by the window is split into two parts -- a downward-going flux, Φ_{FW} [lm], which falls on the floor and portions of the walls below the imaginary horizontal plane passing through the center of the window ("window midplane"), and an upward-going flux Φ_{CW} [lm], which strikes the ceiling and portions of the walls above the window midplane (see Fig. 10). A fraction of Φ_{FW} and Φ_{CW} is absorbed by the room surfaces. The remainder, the first-reflected flux, F_1, is approximated by

$$F_1 = \Phi_{FW}\ \rho_{FW} + \Phi_{CW}\ \rho_{CW} , \tag{20}$$

where ρ_{FW} is the area-weighted average reflectance of the floor and those parts of the walls below the horizontal plane through the window center, and ρ_{CW} is the area-weighted average reflectance of the ceiling and those parts of the walls above the window mid-plane.

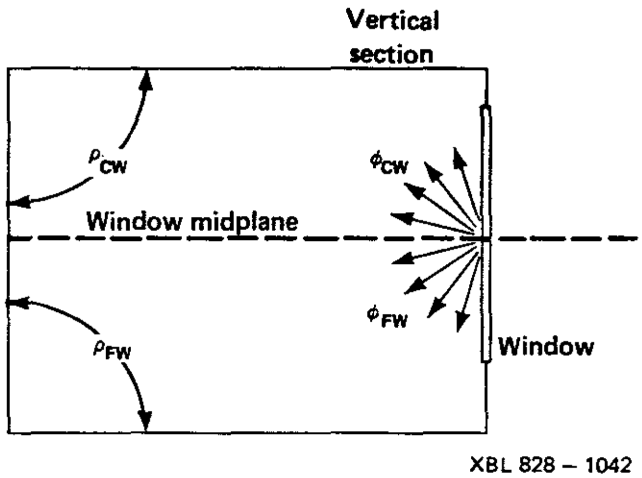

Fig. 10. Vertical section showing up- and down-going transmitted fluxes, ϕ_{CW} and ϕ_{FW}, used in split-flux calculation of the internally-reflected component of interior illuminance.

To find the final average internally-reflected illuminance E_r on the room surfaces (which in this method is uniform throughout the room) a flux balance is used. The total reflected flux absorbed by the room surfaces (or lost through the window(s)) is $AE_r(1 - \rho)$, where A is the total inside surface area of the floors, walls, ceiling, and windows in the room, and ρ is the area-weighted average reflectance of the room surfaces, including windows. From conservation of energy,

$$F_1 = A\ E_r\ (1-\rho) \tag{21}$$

Using Eq. 20,

$$E_r\ [\mathrm{lm/unit\text{-}area}] = \frac{\Phi_{FW}\ \rho_{FW} + \Phi_{CW}\ \rho_{CW}}{A(1-\rho)} \tag{22}$$

This procedure assumes that the room behaves like an integrating sphere with perfectly diffusing interior surfaces and with no internal obstructions. It therefore works best for rooms which are close to cubical in shape, have matte surfaces (which is usually the case), and have no internal partitions. Deviations from these conditions, such as would be the case for rooms whose depth measured from the window-wall is more than three times greater than ceiling height, can lead to substantial inaccuracies in the split-flux calculation.

2.9 Calculation of Average Internal Reflectances

The average reflectances ρ_{CW} and ρ_{FW} in Eq. 22 are calculated as follows. The interior surfaces of EXTERIOR WALLs, ROOFs, INTERIOR-WALLs, UNDERGROUND-FLOORs, and UNDERGROUND-WALLs are divided into three categories according to TILT angle:

"wall" (W) : $10^o \leq$ TILT $\leq 170^o$; floor-wall-ceiling flag = 0;

"ceiling" (C) : $0^o \leq$ TILT $< 10^o$; floor-wall-ceiling flag = 1;

"floor" (F) : $170^o <$ TILT $\leq 180^o$; floor-wall-ceiling flag = 2.

Then

$$\rho_{FW} = \frac{\sum_{i=1}^{N_F} \rho_{F,i} A_{F,i} + \sum_{i=1}^{N_W} \rho_{W,i} A_{W,i} \delta}{\sum_{i=1}^{N_C} A_{F,i} + \sum_{i=1}^{N_W} A_{W,i} \delta} \tag{23}$$

$$\rho_{CW} = \frac{\sum_{i=1}^{N_C} \rho_{C,i} A_{C,i} + \sum_{i=1}^{N_W} \rho_{W,i} A_{W,i} (1-\delta)}{\sum_{i=1}^{N_C} A_{C,i} + \sum_{i=1}^{N_W} A_{W,i} (1-\delta)} \tag{24}$$

$$\rho = \frac{\sum_{i=1}^{N_F} \rho_{F,i} A_{F,i} + \sum_{i=1}^{N_W} \rho_{W,i} A_{W,i} + \sum_{i=1}^{N_C} \rho_{C,i} A_{C,i}}{A} \tag{25}$$

$$A = \sum_{i=1}^{N_F} A_{F,i} + \sum_{i=1}^{N_W} A_{W,i} + \sum_{i=1}^{N_C} A_{C,i} \tag{26}$$

where

N_W, N_C, N_F = number of surfaces in "wall", "ceiling", "floor" categories, respectively,

$\rho_{W,i}$, etc. = inside visible reflectance

$A_{W,i}$, etc. = surface area

$\delta_{W,i}$ = fraction of wall area which lies below the window midplane (ratio of floor-to-window-center height to average floor-to-ceiling height)

The sums in Eq. 23 and 24 exclude the window-wall which is producing the incoming fluxes ϕ_{FW} and ϕ_{CW}. For walls containing windows, the $\rho_{W,i}$ is the area-weighted average reflectance of the opaque and window portions of the wall.

2.10 Calculation of Transmitted Flux from Sky and Ground (Subroutine DREFLT)

The luminous flux incident on the center of the window from a luminous element of sky, ground, or external obstruction at angular position (θ,ϕ), of luminance $L(\theta,\phi)$, and subtending a solid angle $\cos\theta d\theta d\phi$ is

$$d\Phi_{inc} = A_W L(\theta,\phi) \cos\beta \cos\theta d\theta d\phi \quad (27)$$

where A_W is the window area, and $d\Phi_{inc}$ is in lm if L is in cd/ft^2. The transmitted flux is

$$d\Phi = d\Phi_{inc} T(\beta), \quad (28)$$

where $T(\beta)$ is the window transmittance for light at incidence angle β. The value of $T(\beta)$ depends on whether or not the window has a shade and if so, whether the shade is inside or outside the window.

For a bare window, $T(\beta) = \tau_{vis}(\beta)$, the glass visible transmittance. For a window with an interior shading device, $T(\beta) = \tau_{vis}(\beta)\ \tau_{sh}$, where τ_{sh} is the visible transmittance of the shade, which is assumed to be independent of angle of incidence. For a window with an exterior shade, $T(\beta) = \tau_{sh}\tau_{vis,diff}$, where $\tau_{vis,diff}$, is the hemispherical visible transmittance of the glass for diffuse radiation. In this last case, the light transmitted by shade and incident on the glass is assumed to be diffuse, so that $\tau_{vis,diff}$ is used rather than $\tau_{vis}(\beta)$. For the calculation of daylight factors, τ_{sh} is taken to be 1.0. The actual value of the shade transmittance, which can be scheduled, is used in the hourly LOADS calculation.

For a bare window the total downgoing transmitted flux, Φ_{FW}, is obtained by integrating over the part of the exterior hemisphere seen by the window which lies above the window midplane (see Fig. 11). This gives

$$\Phi_{FW,bare} = A_W \int_{\theta_{min}}^{\theta_{max}} \int_{0}^{\pi/2} L(\theta,\phi)\cos\beta T(\beta) \cos\theta d\theta d\phi \quad (29)$$

The upgoing flux is similarly obtained by integrating over the part of the exterior hemisphere which lies below the window midplane:

$$\Phi_{CW,bare} = A_w \int_{\theta_{min}}^{\theta_{max}} \int_{\frac{\pi}{2} - \phi_w}^{0} L(\theta,\phi)\cos\beta T(\beta)\cos\theta d\theta d\phi \tag{30}$$

where ϕ_w is the angle the window outward normal makes with the horizontal plane.

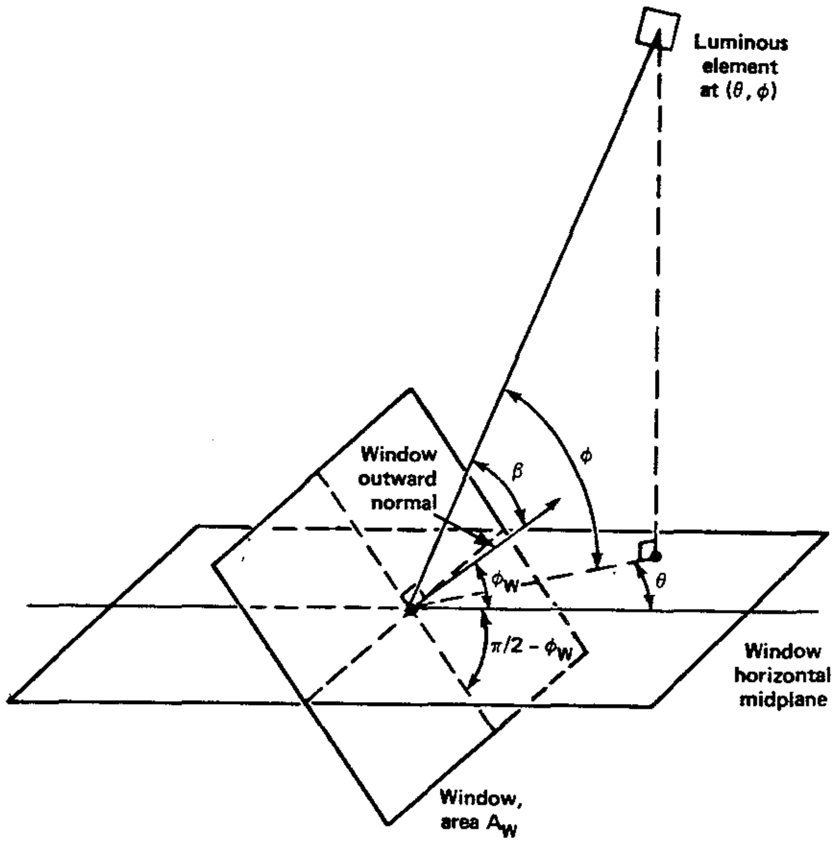

Fig. 11. Geometry for integration over exterior luminance to obtain up- and down-going transmitted flux.

For a window with a diffusing shade, the total transmitted flux is

$$\Phi = A_w \int_{\theta_{min}}^{\theta_{max}} \int_{\frac{\pi}{2} - \phi_w}^{\pi/2} L(\theta,\phi) \cos\beta T(\beta) \cos\theta d\theta d\phi \tag{31}$$

The up- and down-going portions of this flux are

$$\Phi_{FW,sh} = \Phi (1 - f)$$
$$\Phi_{CW,sh} = \Phi f$$

where f is the fraction of the hemisphere seen by the inside of the window which lies above the window midplane. In terms of ϕ_w,

$$f = 0.5 - \phi_w/\pi \tag{32}$$

For a vertical window ($\phi_w=0$), f=0.5 and the up- and down-going transmitted fluxes are equal:

$$\Phi_{FW,sh} = \Phi_{CW,sh} = \Phi/2.$$

For a horizontal skylight ($\Phi_w=\pi/2$), f = 0, giving $\Phi_{FW,sh}=\Phi, \Phi_{CW,sh}=0$.

The limits of integration of θ in Eqs. 29, 30, and 31 depend on ϕ. From Fig. 12 we have, for a window with tilt ϕ_w:

$$\sin \alpha = \sin(A-\pi/2) = \frac{\sin \phi/\tan \phi_w}{\cos \phi},$$

which gives

$$-\cos A = \frac{\tan\phi}{\tan\phi_w},$$

or

$$A = \cos^{-1}\left[-\frac{\tan\phi}{\tan\phi_w},\right]$$

thus,

$$\theta_{min} = -\left|\cos^{-1}(-\tan\phi/\tan\phi_w)\right|,$$

$$\theta_{max} = \left|\cos^{-1}(-\tan\phi/\tan\phi_w)\right|$$

Calculation of Transmitted Flux from Direct Sun

The incident luminous flux from direct sun striking the window is

$$\Phi_{inc} = A_w E_{DN} \cos\beta\ (1-f_{shaded}),\quad \cos\beta\geq 0 \tag{33}$$
$$= 0,\quad \cos\beta<0,$$

where

E_{DN} = direct normal solar illuminance,
A_W = window area,
β = angle of incidence,
f_{shaded} = fraction of window which is shaded by obstructions (fins, overhangs, BUILDING-SHADEs, etc.).

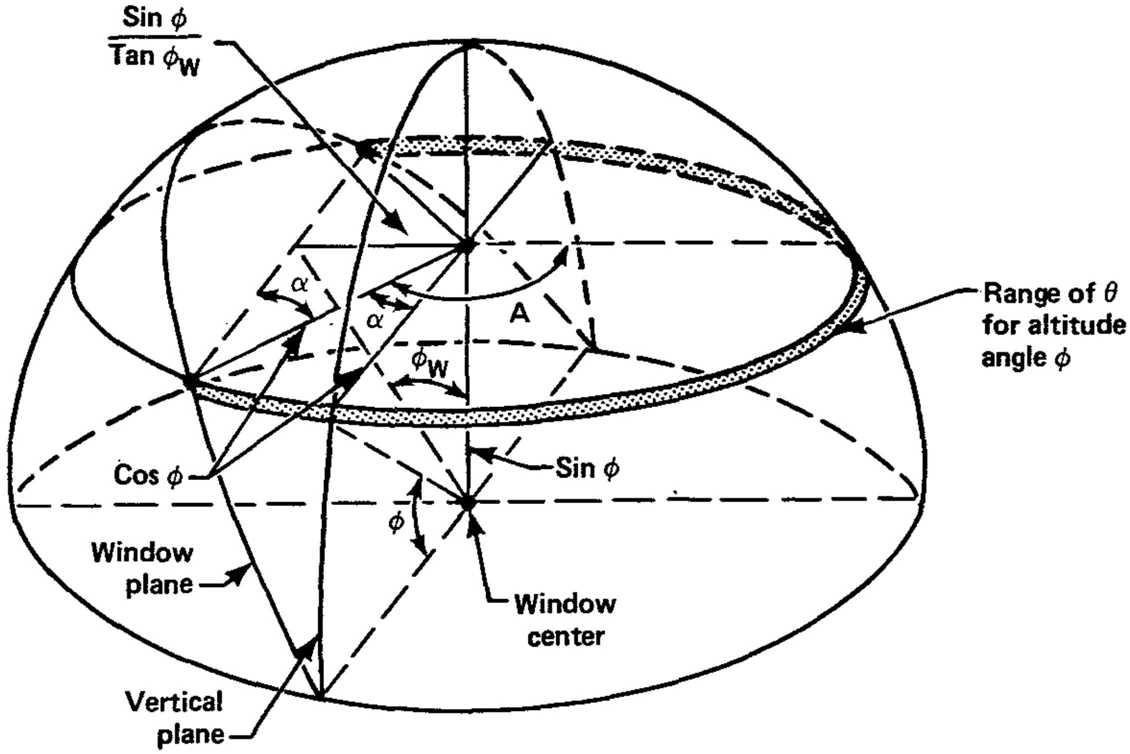

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Fig. 12. Geometry for calculation of integration limits in Eqs. 29, 30, and 31.

The transmitted flux is

$$\Phi = T(\beta)\Phi_{inc},$$

where T (β) is the net transmittance of the window (plus window shade, if present). For a bare window

$$\Phi_{FW,bare} = \Phi ,$$

$$\Phi_{CW,bare} = 0 ,$$

i.e., all of the transmitted flux is downward since the sun always lies above the window midplane. For a window with a diffusing shade,

$$\Phi_{FW,sh} = \Phi\ (1-f),$$

$$\Phi_{CW,sh} = \Phi\ f,$$

where f is given by Eq. 32.

Window Shade Luminance

Window shade luminance is determined at the same time that the transmitted flux is calculated. The shade luminance, incident flux from sky and ground (in lm/ft^2) multiplied by the shade transmittance (which gives ft-L) divided by π (which gives cd/ft^2). For a shade transmittance of 1.0, we then have (compare Eq. 29 and 30).

$$L_{sh}\ [cd/ft^2] = \frac{1}{\pi} \int_{\theta_{min}}^{\theta_{max}} \int_{\frac{\pi}{2}-\phi_w}^{\pi/2} L(\theta,\phi)\cos\beta T_m \cos\beta \cos\theta \, d\theta \, d\phi \tag{34}$$

where

T_m = 1.0 if shade is outside window
= T (β) if shade is inside window

2.11 Daylight Discomfort Glare

The discomfort glare at a reference point due to luminance contrast between a window and the interior surfaces surrounding the window is determined by using the Cornell-BRS "large-source" formula derived by Hopkinson (Refs. 14 and 15). This formula gives

$$G = \frac{L_w^{1.6} \quad \Omega^{0.8}}{L_b + 0.07\ \omega^{0.5}\ L_s} \tag{35}$$

where

G = discomfort glare constant,

L_w = average luminance of the window as seen from the reference point (ft),

ω = solid angle subtended by window with respect to reference point,

Ω = solid angle subtended by the window, modified to take direction of occupant view into account,

L_b = luminance of the background area surrounding the window (ft).

By dividing the window into N_x by N_y rectangular elements, as is done for calculating the direct component of interior illuminance (Sec. 2.7), we have

$$L_w = \frac{\sum_{j=1}^{N_y} \sum_{i=1}^{N_x} L_w(i,j)}{N_x \ N_y}, \tag{36}$$

where L_w (i,j) is the luminance of element (i,j) as seen from the reference point.

Similarly,

$$\omega = \sum_{j=1}^{N_y} \sum_{i=1}^{N_x} d\omega\,(i,j)$$

where $d\omega(i,j)$ is the solid angle subtended by the $(i,j)^{th}$ element with respect to the reference point.

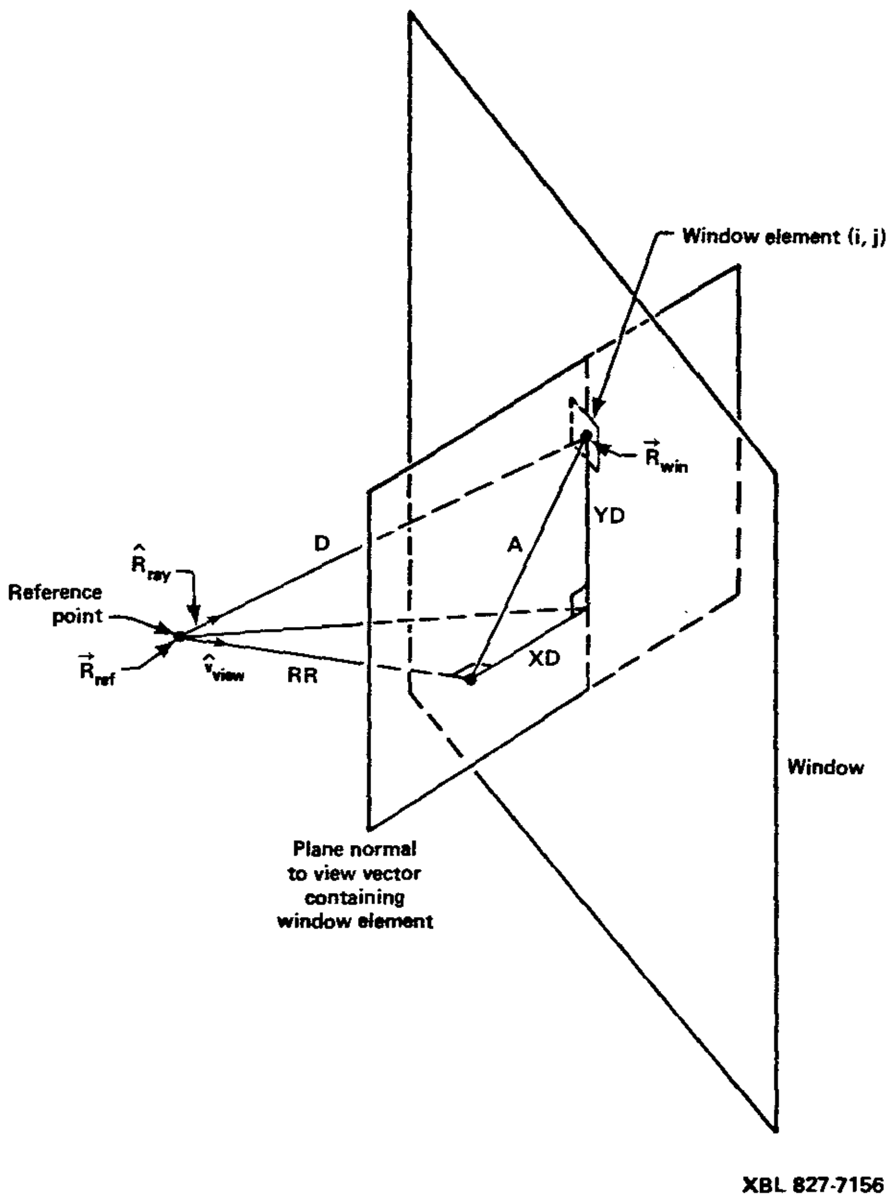

Fig. 13. Geometry for calculation of displacement ratios used in Cornell-BRS glare formula.

The modified solid angle, Ω, is

$$\Omega = \sum_{j=1}^{N_y} \sum_{i=1}^{N_x} d\omega\ (i,j)\ p(x_R, y_R) \tag{37}$$

where p is a "position factor" (Ref. 16) which accounts for the decrease in visual excitation as the luminous element moves away from the line of sight. p depends on the horizontal and vertical displacement ratios x_R and y_R shown in Fig. 13, which are given by

$$x_R\ (i,j) = |A^2 - YD^2|^{1/2}\ /\ RR)$$

$$y_R\ (i,j) = |YD\ /\ RR|\ ,$$

where

$RR = D\ R_{ray} \cdot \hat{v}_{view}$,
$A^2 = D^2 - RR^2$,
$YD = \overline{R}_{win}(3) - \overline{R}_{ref}(3)$.

p can be obtained from graphs given by Petherbridge (Ref. 16) or it can be calculated from tabulated values of p_H, the Hopkinson position factor (Ref. 17), since $p = p_H^{1.25}$. The values resulting from the latter approach are given in Table 5. Interpolation of this table is used in DOE-2 to evaluate p at intermediate values of x_R and y_R.

Table 5.

Petherbridge Position Factor
for Cornell-BRS Glare
Calculation

y_R: Vertical Displacement Factor	x_R : horizontal displacement factor →	0	.5	1.0	1.5	2.0	2.5	3.0	>3.0
	0	1.00	.492	.226	.128	.081	.061	.057	.0
	.5	.123	.119	.065	.043	.029	.026	.023	.0
	1.0	.019	.026	.019	.016	.014	.011	.011	.0
	1.5	.008	.008	.008	.008	.008	.006	.006	.0
	2.0	.0	.0	.003	.003	.003	.003	.003	.0
	>2.0	.0	.0	.0	.0	.0	.0	.0	.0

The background luminance, L_b, is determined by the illuminance E_b and the average reflectance ρ_b of, the floor, wall, and ceiling in the area surrounding the window:

$$L_b = E_b \rho_b$$

ρ_b is taken to be equal to the average interior surface reflectance, ρ, of the entire room. (see Sec. 2.9)

E_b is not explicitly calculated by DOE-2. It is approximated by

$$E_b = \max (E_r , E_s) ,$$

where

E_r = total internally-reflected component of daylight illuminance produced by all the windows in the room (footcandles),

E_s = the illuminance setpoint at the reference point at which glare is being calculated (footcandles).

A precise calculation of E_b is not required since the glare index (see next section) is logarithmic. A factor of two variation in E_b generally produces a change of only 0.5 to 1.0 in the glare index.

2.11.1 Glare Index

The net daylight glare at a reference point due to all of the windows in a room is expressed in terms of a "glare index", G_I, which is given by

$$G_I = 10\log_{10} \sum_{i=1}^{N_W} G_i \qquad (38)$$

where

G_I = glare constant at the reference point due to the i^{th} window,

N_W = number of windows.

The recommended maximum values of G_I, for different situations are given in Table 6 (Ref. 17).

Table 6

Recommended Maximum Daylight Glare Index Values for Different Situations

Location or Building Type	Maximum Daylight Glare Index
Factories	
Rough Work	28
Engine Assembly	26
Fine Assembly	24
Instrument Assembly	22
Laboratories	22
Museums	20
Art Galleries	16
Offices	
General	22
Drafting	20
School Classrooms	20
Hospital Wards	18

2.12 Detailed Description of Preprocessor Subroutine DCOF

The following steps are carried out by DCOF:

1. Set length LWDC of daylight-factor block for each window/reference point combination.

   LWDC = (Number of daylight factors) * (number of clear sky sun positions + number of overcast sky sun positions),

   = 6 * (NPHS * NTHS + 1),

   = 6 * (4 * 5 + 1) = 126,

   where NPHS and NTHS are, respectively, the number of clear-sky solar altitude and azimuth values.

2. First space loop. For each daylit space (DAYLIGHTING=YES):

   a. Check that reference points and zone fractions (fractions of a thermal zone controlled by a reference point) are properly specified for each daylit space. Print error message if:

(1) One or more coordinates of the first reference point are not specified.

(2) Some, but not all, the coordinates of the second reference point are specified.

(3) Sum of zone fractions exceeds 1.0.

(4) Second reference point is specified, but corresponding zone fraction not specified.

b. Find NRF, the total number of reference points (NRF = 1 or 2). Find NWTOT, the number of windows with area greater than 0.1 ft^2 (English input) or 0.1 m^2 (metric input). Print error message if NWTOT = 0.

c. Get space in AA array for daylight factors. The number of words required for each space is

LDCTOT = NRF * NWTOT * LWDC (39)

d. End of first space loop.

3. Get space in AA array for global building-shade luminance blocks. Length of each block is 2*NPHS*NTHS+1.

4. Get space for shadow calculation arrays.

5. Calculate SOLIC(M), the extra-terrestrial direct normal solar illuminance for the first day of each month (Refs. 5 and 6):

SOLIC(M) [footcandles] =

92.9 [126.82 + 4.248 cos(OMJ) + 0.0825 cos(2*OMJ) - 0.00043

cos(3*OMJ) + 0.1691 sin(OMJ) + 0.00914 sin(2*OMJ) + 0.01726 sin(3*OMJ)]

where

M = number of month

OMJ = (2π/366) * (1+ (M-1) * 30.5).

6. For each sun position calculate, for reference month (M=5):

a. Clear sky zenith luminance (subroutine DZENLM)

b. exterior horizontal luminance from sky and from sun for clear and overcast sky (subroutine DHILL)

c. shadow ratios (subroutine SHADOW)

d. global shade luminances for clear and overcast sky (subroutine DSHDLU)

7. Calculate daylight factors. The remainder of the DCOF preprocessor consists of a nested set of 7 loops in the sequence:

   - o space
   - o reference point
   - o exterior wall
   - o window
   - o window x-element
   - o window y-element
   - o sun altitude
   - o sun azimuth

   a. Begin Daylit-Space Loop

   Find area and average reflectance of inside surfaces of space for use in split-flux calculation of inter-reflected illuminance (subroutine DAVREF). See Section 2.9.

   b. Begin Reference Point Loop

   Transform reference points from space coordinate system to building coordinate system (BCS).

   c. Begin Exterior Wall Loop

   (1) Skip wall if a Trombe wall or if wall has no windows.

   (2) Find azimuth of glare view vector in building coordinate system. If this azimuth was not specified, make view vector parallel to first window in space (specifically, set view vector azimuth equal to window azimuth plus 90^{o}).

   (3) Recalculate net area and area*reflectance sum of ceiling, wall, and floor categories with this exterior wall removed.

   d. Begin Window Loop

   (1) Print warning message if window multiplier is not 1.0. Use of a multiplier puts multiple windows all at the same location, which produces erroneous illuminance results.

   (2) Get diffuse transmittance TSOLDF and transmittance at normal incidence TSOLNM for solar radiation.

   TSOLDF = <CAM9>

   TSOLNM = <CAM1> + <CAM2> + <CAM3> + <CAM4>,

   where the <CAMn> are transmission coefficients for the window glass set in subroutine GLYTPO of LDL.

   (3) Print error message if a window-shade has been specified [i.e., WIN-SHADE-TYPE = MOVABLE-INTERIOR, MOVABLE-EXTERIOR, FIXED-INTERIOR, or FIXED-EXTERIOR] but a corresponding visible transmittance schedule (VIS-TRANS-SCH) and shading schedule (SHADING-SCHEDULE) have not been specified.

(4) Print error message if window has VIS-TRANS-SCH or SHADING-SCHEDULE, but WIN-SHADE-TYPE = NONE (the default).

(5) Get W1, W2, and W3, the vertices of the window (in BCS) numbered clockwise starting at upper left as viewed from inside of room (see Fig. 9).

(6) Get

W21	=	unit vector from W2 to W1,
W23	=	unit vector from W2 to W3,
WC	=	center point of window in BCS,
REFWC	=	vector from reference point (RREF) to WC,
WNORM	=	unit vector normal to window, pointing away from room,
ALF	=	absolute value of perpendicular distance between reference point and window plane.

(7) Choose the number of window x-divisions (NWX) and y-divisions (NWY) so that the solid angle subtended by any of the elements with respect to the reference point can be approximated to 1% or better as dA_n/D^2, where dA_n is the projected area of the element and D is the distance from element to reference point. This requires that

$$NWX = \mathrm{int}\ (4 * WW/ALF) \ , \qquad (40)$$

$$NWY = \mathrm{int}\ (4 * HW/ALF) \ ,$$

where WW and HW are the height and width of the window, respectively. An absolute upper limit of 40 is chosen for NWX and NWY to avoid excessive computation time. This yields

NWX = min [40, max(DAY-X-DIVISION, int(4*WW/ALF))]
NWY = min [40, max(DAY-Y-DIVISION, int(4*HW/ALF))]

For example, if WW=40, HW=5, ALF=10, DAY-X-DIVISION=8 (default), and DAY-Y-DIVISION=8 (default),

NWX = min [40, max(8,16)] = 16
NWY = min [40, max(8,2)] = 8

If NWX or NWY from Eq. 40 exceeds 80, a warning message is printed which suggests to the user that the window should be subdivided into two separate windows.

(8) Calculate altitude angle, PHWN, and azimuth angle, THWN, of window outward normal.

(9) For split-flux inter-reflectance calculation (Sec. 2.8 and 2.9):

(a) find ETA, the ratio of floor-to-window center height to average floor-to-ceiling height.

$$ETA = \max\left[0, \min(1, \frac{WC(3) - \langle ZZ\rangle}{\langle ZVOL\rangle / \langle ZFLRAR\rangle}) \right] ,$$

where

$WC(3)$ = z-coordinate of window center in BCS,

$\langle ZZ\rangle$ = z-coordinate of space in BCS,

$\langle ZVOL\rangle$ = volume of space,

$\langle ZFLRAR\rangle$ = floor area of space.

Note that for a horizontal skylight in the ceiling of a rectangular space, ETA=1.

(b) find average inside reflectance, RHOCW, of incident light moving up across window midplane:

$$RHOCW = \frac{(A\rho)_{walls}\ (1-ETA) + (A\rho)_{ceiling}}{A_{walls}\ (1-ETA) + A_{ceiling} + \epsilon} \tag{41}$$

where

$(A\rho)_{walls}$ = sum of area * reflectance of all walls, excluding surface that window is in,

$(A\rho)_{ceiling}$ = area * reflectance of ceiling, excluding surface that window is in,

A_{walls} = total area of all walls, excluding surface that window is in,

$A_{ceiling}$ = area of ceilings, excluding surface that window is in,

$\epsilon = 10^{-5}$, added to prevent zero/zero for a skylight in a rectangular room.

In Eq. 41, $A_{walls}(1-ETA)$ and $(A\rho)_{walls}(1-ETA)$ are the area and area * reflectance of those parts of the walls lying above the window midplane.

(c) find average inside reflectance, RHOFW, of incident light moving down across window midplane:

$$RHOFW = \frac{(A\rho)_{walls}\ ETA + (A\rho)_{floor}}{A_{walls}\ ETA + A_{floor}}$$

(d) find, FRUP, the fraction of light from a window-shade which goes up to the ceiling and part of the walls above window midplane:

$$FRUP = 0.5 - PHWN/\pi$$

For a vertical window (PHWN = 0), FRUP = 0.5, i.e. half of the light transmitted by the shade goes up, and half goes down. For a horizontal skylight (PHWN = $\pi/2$), FRUP = 0, i.e., all of the light transmitted by the shade goes down.

(10) Initialize to zero:

EDIRSK (I,J,K) = sky-related component of direct illuminance at reference point (footcandles),

EDIRSU (I,J,K) = sun-related component of direct illuminance at reference point (footcandles),

AVWLSK (I,J,K) = sky-related component of average window luminance as seen from reference point (cd/ft^2),

AVWLSU (I,J,K) = sun-related component of average window luminance as seen from reference point (cd/ft^2),

where

I = sky condition index: I=1 for clear sky, I=2 for overcast sky;

J = shading device index: J=1 for bare window, J=2 for window covered by shading device;

K = sun position index:
=1 for $\phi_{sun}=10^o$, $\theta_{sun}=290^o$;
=2 for $\phi_{sun}=10^o$, $\theta_{sun}=235^o$;
=3 for $\phi_{sun}=10^o$, $\theta_{sun}=180^o$;
etc.

(11) Initialize to zero:

<OMEGA> = solid angle subtended by window with respect to reference point,

<OMEGAW> = position-factor-weighted solid angle subtended by window.

e. <u>Begin Window x-element Loop</u> (IX=1, NWX)

f. <u>Begin Window y-element Loop</u> (IY=1, NWY)

(1) Find center of window element in BCS:

$$RWIN(I) = W2(I) + (IX - .5) * W23(I) * DWX + (IY - .5) * W21(I) * DWY, \quad I=1,3$$

(2) Find length of ray between reference point and center of window element:

$$DIS = \left[\sum_{I=1}^{3} (RWIN(I) - RREF(I))^2 \right]^{1/2}$$

(3) Construct unit vector along ray pointing from reference point to window element:

$$RAY(I) = (RWIN(I) - RREF(I))/DIS, \quad I=1,3$$

(4) Calculate cosine of "incidence angle", i.e. of angle between ray and window outward normal:

$$COSB = \overline{WNORM} \cdot \overline{RAY}$$

(5) If COSB < 0, light from the window element cannot reach the reference point directly. Skip remaining calculations for this window element.

(6) Find altitude and azimuth of ray in BCS:

$$PHRAY = \sin^{-1}(RAY(3)) \ , \ -\pi < PHRAY < \pi/2$$
$$THRAY = \tan^{-1}(RAY(2),RAY(1)) \ , \ -\pi < THRAY < \pi$$

(THRAY=0 is along x-axis of BCS; PHRAY is measured from x-y plane of BCS).

(7) Find solid angle subtended by window element

$$DOMEGA = DWX * DWY * COSB / D^2$$

Increment solid angle subtended by window:

$$\langle OMEGA\rangle = \langle OMEGA\rangle + \langle DOMEGA\rangle$$

(8) Find POSFAC, the position factor used in the glare calculation:

(a) Initialize POSFAC to zero.

(b) Find distance RR from reference point to point where glare view vector intersects the plane passing through the window-element center which is normal to the view vector:

$$RR = DIS * (\overline{RAY} \cdot \overline{VIEWVC})$$

(c) Find square of distance from intersection point in (b) to window element:

$$ASQ = DIS^2 - RR^2$$

(d) Find vertical displacement of window element with respect to reference point:

$$YD = RWIN(3) - RREF(3)$$

(e) Find horizontal and vertical displacement ratios:

$$XR = |ASQ - YD^2|^{1/2}/RR$$

$$YR = |YD/RR|$$

(f) Get position factor via call to function DPFAC:

POSFAC = DPFAC (XR, YR)

(g) Increment modified solid angle

<OMEGAW> = <OMEGAW> + DOMEGAW * POSFAC

(9) Find variable transmittance of glass, TVISB

TVISB = (VIS-TRANS/TSOLNM) *
[<CAM1> + <CAM2> * COSB + <CAM3>
* COSB^2 + <CAM4> * COSB^3]

(10) Determine if ray from reference point to window element hits a local or global building-shade after passing through window (subroutines DHITSH and DPIERC).

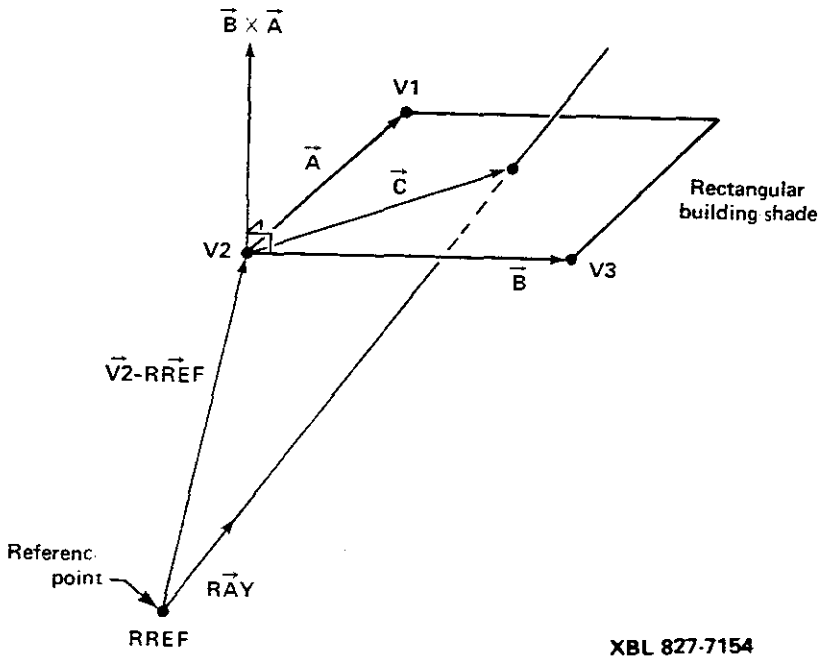

Fig. 14. Geometry for determining if ray from reference point intersects a shading surface (subroutine DPIERC).

From Fig. 14 a ray with a unit vector $\overline{RAY}$ from reference point $\overline{RREF}$ intersects a rectangle with vertices $\overline{V1}$, $\overline{V2}$, and $\overline{V3}$ if

$0 < \overline{C}\cdot\overline{B} < \overline{B}\cdot\overline{B}$,

and

$0 < \overline{C}\cdot\overline{A} < \overline{A}\cdot\overline{A}$,

where

$\overline{C}$ = vector from V2 to point that ray intersects the plane of the rectangle,

$\overline{A} = \overline{V1} - \overline{V2}$,
$\overline{B} = \overline{V3} - \overline{V2}$.

$\overline{C}$ is given by

$$\overline{C} = \overline{RAY} \frac{(\overline{B} \times \overline{A}) \cdot (\overline{V2} - \overline{RREF})}{(\overline{B} \times \overline{A}) \cdot \overline{RAY}} - (\overline{V2} - \overline{RI})$$

g. <u>Begin Sun Altitude Loop (IPHS = 1,NPHS)</u>

(1) Get altitude of sun in degrees (H) and radius (PHSUN)

```
H     = PHSMIN + (IPHS - 1) * PHSDEL
PHSUN = H / 57.3
```

(2) Find clear sky zenith luminance for this solar altitude (subroutine DZENLM).

h. <u>Begin Sun Azimuth Loop (ITHS = 1, NTHS)</u>

(1) get azimuth of sun in BCS

THSUN = (THSMIN - 90 + ITHS * THSDEL) / 57.3 + BAZIM,

where
BAZIM = building azimuth
(THSUN = 0 is along x-axis of BCS)

(2) Calculate sun position index, IHR:

IHR = ITHS + NTHS * (IPHS - 1)

(3) At first step in window element loop (IWX=1, IWY=1) find inter-reflected components of illuminance at reference point, EINTSK and EINTSU, and window shading device luminance, WLUMSK and WLUMSU (subroutine DREFLT).

(4) Add contribution of window element to direct illuminance at reference point and to window luminance:

(a) <u>bare window, building shade not hit</u>
For PHRAY > 0, ray sees sky; therefore for PHRAY > 0,
add DSKYLU * DOMEGA * RAY(3) * TVISB to EDIRSK (I,1,IHR),
add DSKYLU * TVISB to AVWLSK (I,1,IHR),
where DSKYLU is the clear-sky luminance (cd/ft^2) for I=1, and the overcast-sky luminance (cd/ft^2) for I=2.

For PHRAY < 0, ray sees ground; therefore,
Add TVISB * GILSK (I,IPHS) * GNDREF / π to AVWLSK (I,1,IHR),
Add TVISB * GILSU (I,IPHS) * GNDREF / π to AVWLSK (I,1,IHR),

where GILSK and GILSU are the illuminances on the ground due to sky and sun, respectively, in cd/ft^2. Note that EDIRSK does not appear in this case since light from the ground cannot directly reach the horizontal workplane.

(b) bare window, building shade hit
Add TVISB * (building shade luminance, sky) to AVWLSK (I,1,IHR) for I=1, clear sky; and 2, overcast sky (IHR = 1 only).

Add TVISB * (building shade luminance, sun) to AVWLSU (I,1,IHR) for I=1, clear sky.

If PHRAY > 0, add (building shade luminance, sky) *DOMEGA*RAY(3)*TVISB to EDIRSK (I,1,IHR) for I=1,2

add (building shade luminance, sun) *DOMEGA*RAY(3)*TVISB to EDIRSU (I,1,IHR) for I=1,2

In this last case, window elements which lie below the horizontal plane containing the reference point (and therefore have PHRAY < 0) are excluded since light from these elements cannot reach the reference point directly.

(c) Window with shade

In this case, the luminance of the window element is equal to the shade luminance (times the glass transmittance if the shade is on the outside of the window).

- Set transmittance multiplier:
  TVIS1 = 1.0 if shade inside window,
  = TVISB if shade outside window.
- Add WLUMSK (I,INR) * TVIS1 to AVWSLK (I,2,IHR) for I=1, clear sky; and 2, overcast sky (IHR=1 only)
- Add WLUMSU (I,INR) * TVIS1 to AVWSLU (I,2,IHR) for I=1, clear sky; and 2, clear sky (IHR=1 only),

where
WLUMSK is the luminance of the shade (cd/ft^2) due to light directly from sky or light from sky reflected from ground or building shades; and WLUMSU is the corresponding sun-related luminance. Note that at this stage the shade transmittance is taken to be 1.0. Correction for the actual transmittance, which is a scheduled quantity, is done in the hourly calculation.

If PHRAY > 0,

- Add WLUMSK (I,IHR) * DOMEGA * RAY(3) * TVIS1 to EDIRSK (I,2,IHR) for I=1, clear sky; and for I=2, overcast sky (IHR=1 only).
- Add WLUMSU (I,IHR) * DOMEGA * RAY(3) * TVIS1 to EDIRSU (I,2,IHR) for I=1, clear sky.

i. <u>End of Sun Azimuth Loop.</u>

j. <u>End of Sun Altitude Loop.</u>

k. <u>End of Window y-element Loop.</u>

l. <u>End of Window x-element Loop.</u>

m. Loop again over sun positions and calculate the sky- and sun-related daylight factors by adding direct and inter-reflected illuminance components, then dividing by the exterior horizontal illuminance.

The illuminance factors are:

$$\text{DFACSK [fc/fc]} = \frac{\text{EDIRSK (I,J,IHR) + EINTSK (I,J,IHR)}}{\text{GILSK (I,IPHS)}} ,$$

$$\text{DFACSU [fc/fc]} = \frac{\text{EDIRSU (I,J,IHR) + EINTSU (I,J,IHR)}}{\text{GILSU (I,IPHS)}} .$$

The window luminance factors are:

$$\text{SFACSK [ft-L/fc]} = \frac{\text{AVWLSK (I,J,IHR)} *\pi \text{ /(NWX * NWY)}}{\text{GILSK (I,IPHS)}} ,$$

$$\text{SFACSU [ft-L/fc]} = \frac{\text{AVWLSU (I,J,IHR)} *\pi \text{ /(NWX * NWY)}}{\text{GILSU (I,IPHS)}} .$$

The window background-luminance factors are:

$$\text{BFACSK [ft-L/fc]} = \frac{\text{EINTSK (I,J,IHR) * RHOAV}}{\text{GILSK (I,IPHS)}} ,$$

$$\text{BFACSU [ft-L/fc]} = \frac{\text{EINTSU (I,J,IHR) * RHOAV}}{\text{GILSU (I,IPHS)}} ,$$

where RHOAV is the area-weighted average inside surface reflectance of the space.

n. Print daylight factor summary report (LV-L) for this space-window-reference point combination. Note that if a window-shade is defined, it is assumed in this report to have transmittance=1.0.

o. Store daylight factors in AA array after packing the pairs (DFACSK, DFACSU), (BFACSK, BFACSU), and (SFACSK, SFACSU) to save space.

p. End of window loop.

q. End of exterior wall loop.

r. End of space loop.

3. Hourly Daylighting Calculation

3.1 Overview

An hourly daylighting calculation is performed each hour that the sun is up for each space with DAYLIGHTING=YES. The exterior horizontal illuminance from sun and sky is calculated theoretically for the current-hour sun position and cloud amount, or is determined from solar irradiance data if present on the weather file. The interior illuminance at each reference point is found for each window by interpolating the illuminance factors calculated by the preprocessor. By summation, the net illuminance and glare due to all the windows in a space are found. If glare exceeds MAX-GLARE, window shading devices are deployed, if present, to reduce glare. Finally, the illuminance at each reference point for the final window-shade configuration is used by the lighting control system simulation (subroutine DLTSYS) to determine the electric lighting power required to meet the illuminance setpoint at each reference point.

3.2 Calculation Sequence

The following calculations are performed if there is at least one daylit space.

3.2.1 Exterior Daylight Availability Calculation

1. Integrate over sky luminance distribution to find exterior horizontal illuminance in footcandles from standard CIE clear sky (CHILSK), and from standard CIE overcast sky (OHILSK). Find direct solar CIE horizontal illuminance (CHILSU). These calculations use the current-hour sun position and are performed only on the first day of each month using the appropriate monthly value of atmospheric moisture and turbidity as entered with the ATM-MOISTURE and ATM-TURBIDITY keywords (subroutines DAVAIL, DHILL, DSKYLU, DNSOL, DZENL).

2. If weather file has measured solar irradiance data, find lumens/watt conversion factors for direct and diffuse radiation from CIE clear sky (CDIRLW, CDIFLW, respectively) and from CIE overcast sky (ODIFLW) (subroutines DAVAIL, DLUMEF).

3. For the current sky condition, which will be either clear, partly-cloudy, or overcast, the sky is divided into a fraction ETACLD which has the CIE clear sky luminance distribution for the current sun position, and a fraction 1-ETACLD which has the CIE overcast sky luminance distribution. ETACLD is a function of CR, the fraction of the skydome covered with clouds (obtained from the weather file).

   The form chosen for ETACLD vs CR, shown in Fig. 15, gives a clear sky luminance distribution for the whole sky for CR $\leq$ 0.2, which assumes that, for low cloud amounts, reflection of sunlight from the clouds will, on the average, give a cloud luminance which is comparable to that of the sky. As CR increases above 0.2, the average cloud luminance is assumed to become progressively closer to the CIE overcast sky luminance.

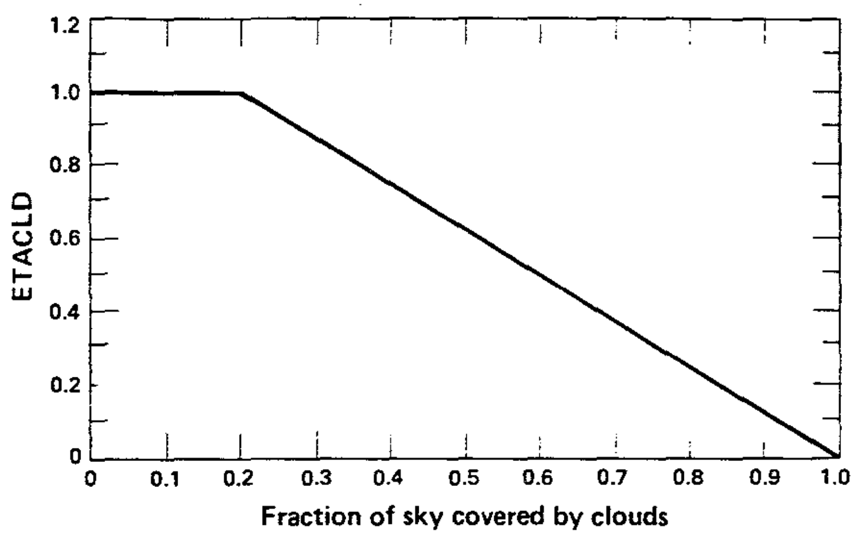

Fig. 15. ETACLD factor.

We have then:

CHISKF[footcandles] = exterior horizontal illuminance due to fraction of sky which has clear sky luminance distribution
= ETACLD * CHILSK (IHR)

OHISKF[footcandles] = exterior horizontal illuminance due to fraction of sky which has overcast sky luminance distribution
= (1-ETACLD) * OHILSK (IHR)

HISUNF[footcandles] = average direct solar exterior horizontal illuminance for the current hour
= (1-CR) * CHILSU (IHR)

If the weather file has measured solar radiation data, the above direct solar illuminance is replaced by

HISUNF = RDNCC * 0.292875 * CDIRLW * RAYCOS(3)

where

RDNCC = measured direct normal solar irradiance [Btu/ft^2-h],

0.292875 = conversion factor for Btu/ft^2-h to w/ft^2,

CDIRLW = luminous efficacy of direct solar radiation for current hour [lm/w],

RAYCOS = cosine of angle of incidence on the horizontal.

In addition, CHISKF and OHISKF are adjusted so that their sum equals the measured horizontal diffuse irradiance, SDIFH, times the luminous efficacy. Thus

CHISKF $\rightarrow$ CHISKF * ALFAD
OHISKF $\rightarrow$ OHISKF * ALFAD

where

$$\text{ALFAD} = \frac{\text{SDIFH * (CDIFLW*ETACLD + ODIFLW*(1-ETACLD))}}{\text{CHISKF + OHISKF}}$$

3.2.2 Luminous Efficacy of Solar Radiation

If solar radiation values are present on the weather file, the luminous efficacy in lumens/watt is calculated for direct solar radiation, clear sky diffuse solar radiation, and overcast sky diffuse solar radiation.

Luminous Efficacy, Direct Solar Radiation

The luminous efficacy of direct solar radiation as parameterized by Dogniaux (Refs. 5 and 6) is

$$K_s \text{ [lm/W]} = K_o \, e^{-mT(\bar{a}_R - \bar{a}_s)} \tag{42}$$

where
K_o = 93.73 lm/W, the extraterrestrial luminous efficacy,
m = optical air mass, given by Eq. 11,
T = atmospheric turbidity, given by Eq. 6,
$\bar{a}_R$ is given by Eq. 10,

and

$$\begin{aligned}\bar{a}_s = {} & 1.4899 - 2.1099 \cos \phi_{sun} + 0.6322 \cos 2\phi_{sun} \\ & + 0.0252 \cos 3\phi_{sun} - 1.0022 \sin \phi_{sun} \\ & + 1.0077 \sin 2\phi_{sun} - 0.2606 \sin 3\phi_{sun}\end{aligned}$$

K_s is plotted as a function of solar altitude for selected values of turbidity coefficient, β, and atmospheric moisture, w, in Fig. 16. The rapid fall-off in K_s for solar altitudes $\leq$30% is primarily due to the λ^{-4} wavelength dependence of Rayleigh scattering.

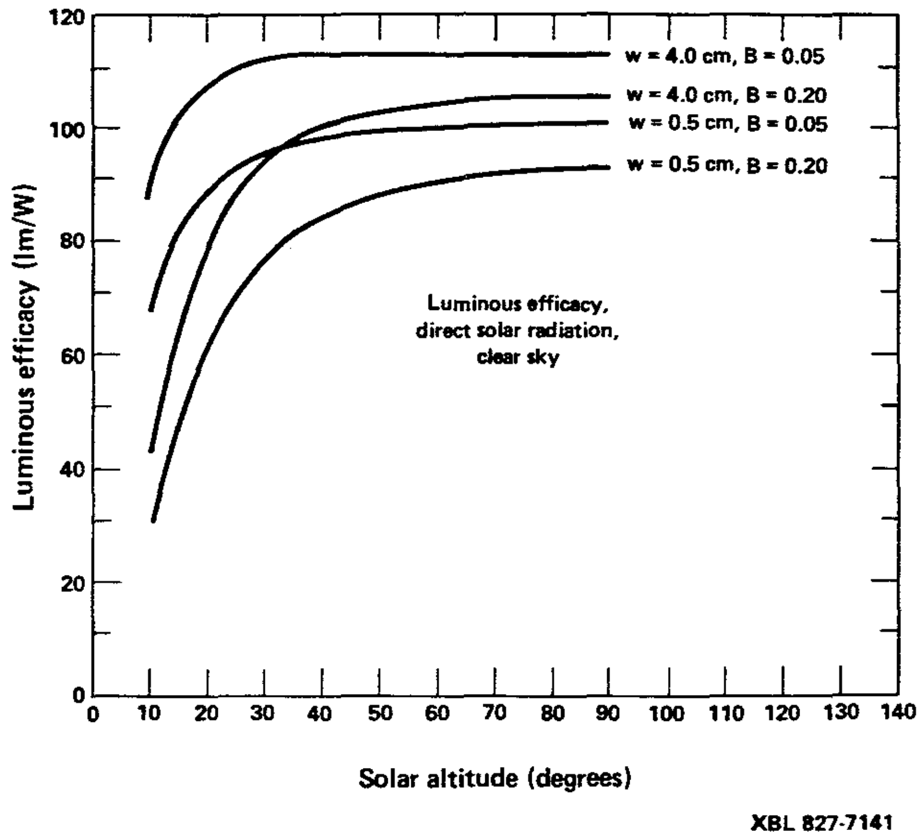

Fig. 16. Luminous efficacy of direct solar radiation for clear sky conditions, for selected values of atmospheric moisture, w and decadic turbidity coefficient, B ($B \cong 1.07\ \beta$).

Luminous Efficacy, Diffuse Solar Radiation, Clear Sky

Figure 17, which is based on Table 4 of Aydinli, Ref. 19, shows the luminous efficacy, K_{cl}, of clear sky diffuse radiation as a function of β, w, and solar altitude. Aydinli's values are based on calculations (Refs. 18 and 20) taking into account the spectral distribution of extraterrestrial solar radiation, Rayleigh scattering, aerosol scattering and absorption by water vapor and ozone. The figure shows that K_{cl} varies from 115 to 135 lm/w, with a mean value of 125.4 lm/w and standard deviation of 6.1 lm/w. Because of the relatively small standard deviation in K_{cl} (~±5%) the mean value of K_{cl} is used in DOE-2.

Luminous Efficacy, Diffuse Solar Radiation, Overcast Sky

A constant value of 110 lm/w (Ref.6) is used for the luminous efficacy of diffuse solar radiation from an overcast sky.

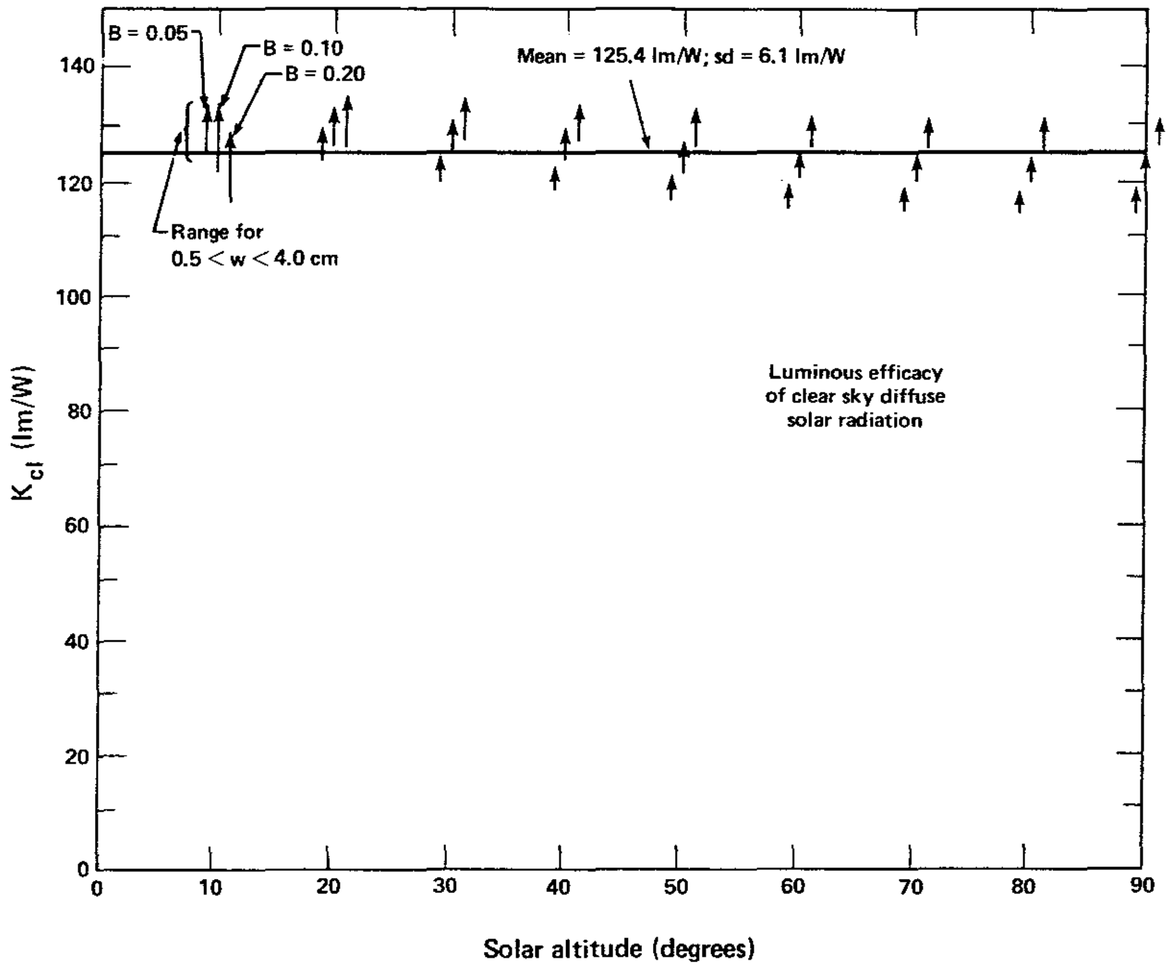

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Fig. 17. Luminous efficacy of clear sky diffuse solar radiation as a function of solar altitude, decadic turbidity factor, B (B ≅ 1.07 β), and atmospheric moisture, w. Based on Aydinli [Ref. 19].

3.2.3 Interior Illuminance Calculation (Subroutine DINTIL)

The following calculations are performed for each daytime hour for each daylit space.

1. Begin first window loop. Get shade transmittance, TAU, of window shading device.

2. Begin first reference point loop. Using current-hour sun position, unpack and interpolate stored daylight factors to obtain

DFSKHR (I,IS) = sky-related illuminance factor [fc/fc]
DFSUHR (I,IS) = sun-related illuminance factor [fc/fc]
BFSKHR (I,IS) = sky-related window-background luminance factor [ft-L/fc]
BFSUHR (I,IS) = sun-related window-surround luminance factor [ft-L/fc]
SFSKHR (I,IS) = sky-related window luminance factor [ft-L/fc]
SFSUHR (I,IS) = sun-related window luminance factor [ft-L/fc]

Here I = 1 for clear sky
       2 for overcast sky
  IS = 1 for bare window
       2 for window with shading device

3. Multiply above daylight factors by exterior horizontal illuminance (and by shading device transmittance for shaded-window case) to obtain interior illuminance due to this window, <ILLUMW>; window background luminance, <ILLUMW>; and average window luminance, <SLUMW>:

$$\langle ILLUMW \rangle_{IL,IS} = [DFSUHR(1,IS) * HISUNF + DFSKHR(1,IS) * CHISKF + [DFSKHR(2,IS) * OHISKF] * TAU1$$

$$\langle BLUMW \rangle_{IL,IS} = [BFSUHR(1,IS) * HISUNF + BFSKHR(1,IS) * CHISKF + [BFSKHR(2,IS) * OHISKF] * TAU1$$

$$\langle SLUMW \rangle_{IL,IS} = [SFSUHR(1,IS) * HISUNF + SFSKHR(1,IS) * CHISKF + [SFSKHR(2,IS) * OHISKF] * TAU1$$

where IL = 1,2 is the reference point index
  TAU1 = 1 for IS=1 (bare window)
       = TAU, the shade transmittance, for IS=2 (window with shading device)

4. End of first reference point loop.

5. End of first window loop.

6. Find total interior illuminance and background luminance due all windows in the space. At this point, a shading device covers a window only if (a) a fixed shading device has been defined (WIN-SHADE-TYPE=FIXED-INTERIOR or FIXED-EXTERIOR), or (b) the user has specified solar gain control by inputting a MAX-SOLAR-SCH for the window, and the direct solar radiation transmitted through the window this hour (calculated in subroutine CALEXT) exceeds the MAX-SOLAR-SCH value, and the sun control probability tests passes.

The total interior illuminance at reference point IL is then

$$\langle DAYLIGHT\text{-}ILLUM \rangle_{IL} = \sum_{windows} \langle ILLUMW \rangle_{IS,IL} ,$$

where IS = 1 if window is bare
          = 2 if shading device covers window

The total background luminance is

$$BACLUM(IL) = \sum_{windows} \langle BLUMW \rangle_{IS,IL}$$

3.2.4 Glare Index Calculation

Find glare index GLRNDX(IL) at each reference point via call to subroutine DGLARE. This yields

$$\mathrm{GLRNDX(IL)} = 10 \log_{10} \sum_{\mathrm{windows}} \frac{\langle \mathrm{SLUMW} \rangle_{\mathrm{IS,IL}}^{1.6} \ \langle \mathrm{OMEGAW} \rangle_{\mathrm{IL}}^{0.8}}{\mathrm{BACL} + 0.07 \langle \mathrm{OMEGA} \rangle_{\mathrm{IL}}^{0.5} \langle \mathrm{SLUMW} \rangle_{\mathrm{IL,IS}}} \qquad (43)$$

where

$\langle \mathrm{OMEGAW} \rangle_{\mathrm{IL}}$ = weighted solid angle subtended by window
$\langle \mathrm{OMEGA} \rangle_{\mathrm{IL}}$ = solid angle subtended by window
BACL = background luminance
= max (BACLUM(IL), RHOAV * SETPNT(IL))

In the last relationship, the background luminance is approximated as the larger of the background luminance from daylight, and the average background luminance which would be produced by the electric lighting at full power if the illuminance on the room surfaces were equal to the setpoint illuminance, SETPNT(IL). In a more detailed calculation, where the luminance of each room surface is separately determined by a multi-surface flux balance, BACL would be better approximated as an area-weighted luminance of the surfaces surrounding a window, taking into account the luminance contribution from the electric lights.

3.2.5 Glare Control Logic

If glare at either reference point exceeds <MAX-GLARE>, close shading devices one by one in an attempt to bring the glare at both points below <MAX-GLARE>. (Each time a shading device is closed, the glare and illuminance at each reference point is recalculated.) The following logic is used:

1. If there is one reference point, close a shade if it decreases the glare, even if it does not decrease the glare below MAX-GLARE.

2. If there are two reference points:

   (a) if glare is too high at both points, close a shade if it decreases glare at both points.

   (b) if glare is too high only at the first point, close a shade if the glare at the first point decreases, and the glare at the second point stays below MAX-GLARE.

   (c) if glare is too high only at the second point, close a shade if the glare at the second point decreases, and the glare at the first point stays below MAX-GLARE.

3. A shade is left open if the glare-control probability test fails, i.e., if a random number between 0 and 1 is greater than GLARE-CTRL-PROB. For example, if GLARE-CTRL-PROB=0.8, there is a 20% chance the shade will remain open even if closing it reduces glare.

4. Shades are closed in the order of window input until glare at both points is below MAX-GLARE, or until there are no more shades.

3.2.6 Lighting Control System Simulation (Subroutine DLTSYS)

1. For each reference point, calculate the fractional electric lighting output power, FP, required to meet the illuminance setpoint, SETPNT. FL, the fractional light output required to meet the setpoint, is given by

$$FL = \frac{SETPNT(IL) - \langle DAYLIGHT\text{-}ILLUM\rangle_{IL}}{SETPNT(IL)},$$

   where
   IL = reference point index
   $\langle DAYLIGHT\text{-}ILLUM\rangle_{IL}$ = daylight illuminance (fc) at reference point IL

   If $\langle DAYLIGHT\text{-}ILLUM\rangle_{IL} > SETPNT(IL)$, FL=0.

2. For a continuously-dimmable control system, it is assumed that FP is constant equal to MIN-POWER-FRAC for FL < MIN-LIGHT-FRAC and that FP increases linearly from MIN-POWER-FRAC to 1.0 as FL increases from MIN-LIGHT-FRAC to 1.0 (see Fig. 18a). This gives

$$\begin{aligned} FP &= \text{MIN-POWER-FRAC for } FL \le \text{MIN-LIGHT-FRAC} \\ &= \frac{FL + (1-FL)(\text{MIN-POWER-FRAC}) - (\text{MIN-LIGHT-FRAC})}{1-(\text{MIN-LIGHT-FRAC})} \text{ for} \\ &\qquad \text{MIN-LIGHT-FRAC} \le FL \le 1 \end{aligned}$$

3. For a stepped control system, FP takes on discrete values depending on the range of FL and the number of steps, LIGHT-CTRL-STEPS (see Fig. 18b). (Note that LIGHT-CTRL-STEPS is the number of steps in FP excluding FP=0). This gives:

$$\begin{aligned} FP &= 0, \text{ if } FL = 0 \\ &= \frac{\text{int }[(\text{LIGHT-CTRL-STEPS}) * FL] + 1}{\text{LIGHT-CTRL-STEPS}} \text{ for } 0<FL<1 \\ &= 1, \text{ if } FL = 1 \end{aligned}$$

   To simulate the uncertainty involved with manual switching of lights, FP is set one level higher a fraction of the time equal to 1-(LIGHT-CTRL-PROB). Specifically, if FP<1,

FP → FP + 1/(LIGHT-CTRL-STEPS)

if a random number between 0 and 1 exceeds LIGHT-CTRL-PROB. The default value of 1 for LIGHT-CTRL-PROB implies automatic switching with no probabilistic element.

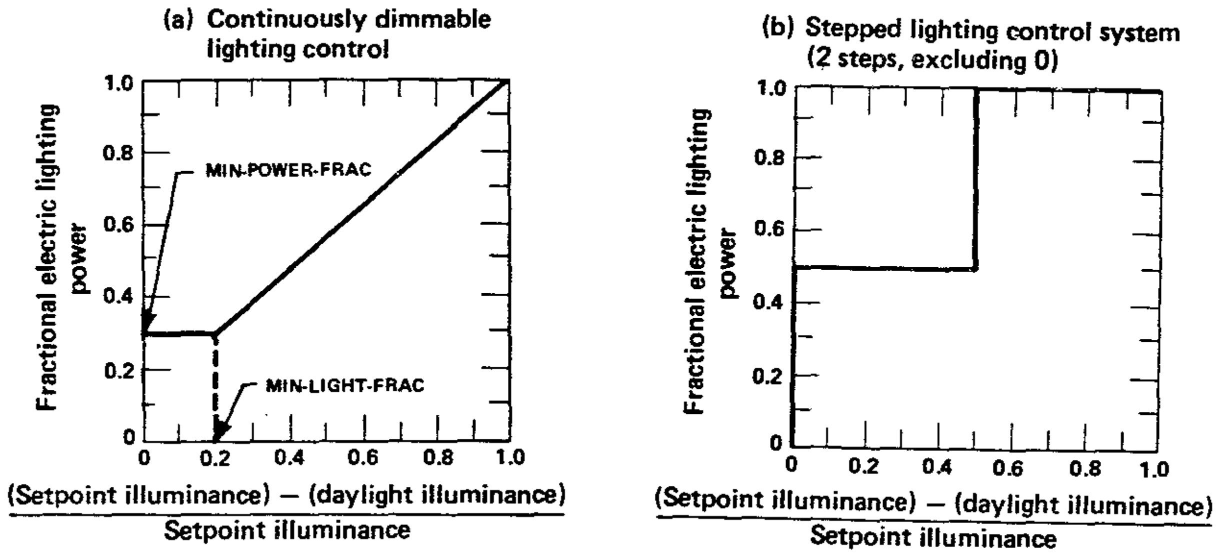

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Fig. 18. Lighting control curves for (a) continuously dimmable system and (b) stepped system.

4. FP is corrected for the fraction, FSUNUP, of the hour that the sun is up (FSUNUP=1 if sun is up for the entire hour; FSUNUP<1 for sunrise and sunset hours.)

   FP → FP * FSUNUP + 1.0 * (1-FSUNUP)

   It is assumed that the exterior illuminance before sunrise is zero.

5. Using the value of FP at each reference point, and the fraction ZFRAC of the space controlled by the reference point, the net lighting power multiplier for the entire space is calculated:

$$\langle \text{POWER-RED-FAC} \rangle = \sum_{\text{ref.pts.}} \text{FP*ZFRAC} + 1.0 * \left[1 - \sum_{\text{ref.pts.}} \text{ZFRAC} \right]$$

   In this expression, the term on the right in parentheses corresponds to the fraction of the space not controlled by either reference point. For this fraction, which is generally zero, the electric lighting is unaffected and the power multiplier is 1.0.

   Note that the fractional <u>reduction</u> in lighting power due to daylighting is 1-<POWER-RED-FAC>.

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