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OCD Work Unit 1215A

SUMMARY
OF
RESEARCH REPORT

SHELTER ENVIRONMENTAL PREDICTION (SHEP) COMPUTER CODE

MODIFICATION 3

USER'S MANUAL

GARD Final Report 1423 June 1968

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General American Research Division
General American Transportation Corporation

REVIEW NOTICE

This report has been reviewed in the Office of Civil Defense and approved for publication. Approval does not signify that the contents necessarily reflect the views and policies of the Office of Civil Defense.

INTRODUCTION

The Shelter Environmental Prediction (SHEP) computer code will calculate the environmental response of a shelter, or any large structure, to time-varying thermal loads and ventilation inlet psychrometric conditions. Shelter conditions computed by finite difference methods define the history of the shelter environment during occupancy.

The SHEP code accommodates solar radiation, boundary surface heat transfer, moisture evaporation or condensation on the boundaries, equipment and lighting loads, and air conditioning. Little technical knowledge of mass or energy transfer is required by a user of the SHEP code. Information that must be supplied to the code includes shelter physical, thermal and geometrical characteristics, occupancy levels and durations, and hourly inlet conditions.

The shelter model used in the code is based upon the assumptions that:

1. Air within the shelter and ventilation air is completely and instantaneously mixed, so that one psychrometric condition will completely specify the shelter environment;
2. Moisture condensation and evaporation is filmwise with the convective heat transfer coefficients constant over each boundary surface, but variable from boundary to boundary.
3. Radiative energy transfer between the shelter boundaries is neglected.
4. Shelter exhaust air is at the psychrometric condition of the shelter atmosphere; and
5. Thermal and physical properties of the air and of the structural materials are not temperature-dependent.

The SHEP code permits the analysis of an actual shelter with up to 20 different boundaries, enclosing a volume which the sensible and latent energy exchange with the environment external to the shelter.

The user's manual explains the various features of the SHEP code, presents the input and output formats, gives representative input data values, and includes an application of the code to a typical shelter structure.

The code is written in FORTRAN IV specifically for the CDC 3600 computer system and consists of 78 cards. It requires a memory bank of at least 65^k words (each word of 48 bits) for the code and the accompanying matrices.

FEATURES OF THE PROGRAM

The shelter model used by the SHEP code is an accurate description of the actual shelter under analysis because of the methods which have been formulated in the code to handle the thermal processes which affect the shelter environment. These processes include:

1. solar radiation,
2. air conditioning,
3. moisture evaporation and condensation,
4. time-varying inlet conditions, and
5. boundary heat transfer.

It has been found that during extreme hot weather, many actual shelters respond as if they had adiabatic boundaries. Thus, the code has the ability of analyzing a shelter with adiabatic or non-adiabatic shelter boundaries.

Shelter Boundaries

An actual shelter is bounded by walls, floor and ceiling, composed of several different kinds of materials (e.g., cement, glass, metal, etc.) and

these can be at any orientation (slope and azimuth). In addition, the exterior boundary surface may be exposed to various media (e.g., air, soil, etc.). An implicit finite-difference approach based upon a one-dimensional node array is used to compute temperature distribution across a boundary. This nodal point approach to the temperature profile across the boundary permits an implicit representation of the temperature through the boundary by applying an energy balance at each of n nodes. The heat transfer through a non-adiabatic boundary due to conduction may then be computed based on the interior boundary surface temperatures. This implicit procedure does not have the stability considerations associated with the explicit method. Thus, longer time intervals can be utilized at each finite difference increment.

If the boundaries are considered adiabatic, heat transfer both through the boundary and due to condensation or evaporation on the surface are considered zero.

Solar Radiation

If a surface is exposed to ambient air, it will normally be exposed to direct, diffuse and/or reflected solar radiation. If the surface is a shelter boundary, the incident radiation will serve to raise the shelter temperature in two ways. First, incident radiation will be partially absorbed by the boundary, thus raising its temperature and, in time, the temperature of the shelter. Second, radiation transmitted through the boundary will be incident on interior surfaces, similarly raising their temperatures and that of the shelter atmosphere.

SHEP makes several simplifying assumptions in treating the effects of solar radiation. First, incident radiation absorbed by each boundary is

considered a surface phenomenon. Second, all reflected radiation, both that which falls onto the shelter surfaces from surrounding objects and that which is reflected from the shelter surfaces, is neglected. Also, radiation transmitted through a boundary is considered an instantaneous thermal load inside the shelter, similar to the lighting and equipment loads.

Air Conditioning

In a typical air conditioning unit, warm air passes over cooling coils, thereby lowering its dry-bulb temperature through convective heat exchange and lowering its moisture content through condensation. The temperature of the coils is not constant, but varies as a function of load. Typically, all the air passing through the air conditioner does not experience these heat and mass transfer processes due to flow turbulence.

The method the SHEP code utilizes to calculate the air conditioning load assumes that the temperature of the coils and the percentage of air unaffected by passing through the unit do not vary with the cooling load. An "effective coil surface temperature" is assumed as the design temperature of the coils; and a "coil bypass factor" is the design value of the percentage of air unaffected by the cooling units. If these two parameters are both assumed constant, the air conditioning performance of an actual unit can be estimated reasonably well.

The ventilation rates of outside air entering the system, of air passing through the air conditioning unit, and of air entering the shelter must all be specified by the code user. Therefore, the mixing processes can be altered, or even eliminated, by varying the various ventilation rates.

Air conditioning removes both sensible and latent energy. This energy removal, ΔQ, is given by

$$\Delta Q = c_p \dot{m} \Delta T + h_{fg} \dot{m} \Delta W$$

where

c_p = specific heat of air 0.24 Btu/lb-°F

$\dot{m}$ = mass flow rate of dry air through the air conditioning unit, lb/hr

ΔT = temperature difference across the unit, °F

h_{fg} = heat of condensation of water vapor, Btu/lb water

ΔW = humidity ratio difference across the unit, lb water/lb dry air

Moisture Condensation

Whenever the vapor pressure at the interior surface of a boundary is lower than the vapor pressure of the shelter atmosphere, moisture will migrate to and condense on the surface, thereby removing energy from the shelter environment. If, at another time, the vapor pressure at the boundary surface is higher than the vapor pressure of the shelter air, the process will be reversed and condensed water on the surface will re-evaporate and migrate into the shelter atmosphere.

If sufficient moisture condenses, it will run down the walls and accumulate on the floor of the shelter. Since the SHEP code assumes that condensation occurs in an even film on an interior surface, the effect of gravity is neglected.

The amount of energy transfer due to moisture condensation is given by

$$Q_{condensation} = 2.825 \frac{\lambda h}{\rho_a} \left(\frac{p_o}{p_b - p_o} - \frac{p_s}{p_b - p_s} \right)$$

where

λ = heat of condensation

h = film heat transfer coefficient

ρ_a = density of dry air

p_o = partial pressure of water vapor at shelter temperature

p_b = barometric pressure

p_s = partial pressure of water vapor at wall temperature

Evaporation is assumed to be the exact opposite of condensation and, therefore, the same equation applies.

Metabolic Loads

The metabolic expressions of Houghten are adopted in this study, since they reflect effects of relative humidity in the shelter. They are given by

$$Q_{sensible} = -0.06875(T_{db})^2 + 1.625(T_{db}) + 523.0 \quad \text{for } T_{db} \geq 50°F$$

$$Q_{total} = \begin{cases} -1.482\ (ET) + 514.0 & \text{for } 50°F \leq ET \leq 87°F \\ -1.508\ (ET)^2 + 259.7\ (ET) - 10795.2 & \text{for } 87°F < ET \leq 102°F \\ 0.0\ \text{(assumed)} & \text{for } ET > 102°F \end{cases}$$

with $Q_{latent} = Q_{total} - Q_{sensible}$, assuming that the body is in thermal equilibrium with the shelter environment, and hence, neglecting the heat storage term.

Varying Inlet Conditions

The psychrometric condition of the shelter atmosphere and of the entering ventilation air are considered by the code as a function of dry-bulb temperature and relative humidity, which normally vary with time.

Certain other factors which affect the shelter atmosphere and which normally vary are:

1. the number of occupants,
2. the ventilation rate, and
3. the lighting and equipment loads.

In the code, these factors may have different values for each hour of occupancy.

Determination of Shelter Dry-Bulb Temperature

All thermal loads and enthalpies are computed at the beginning of a time increment based upon an estimate of what the shelter dry-bulb temperature will be. Then the net amount of energy added to the shelter system during that increment is calculated and from it, the shelter dry-bulb temperature. Since the shelter dry-bulb temperature of the increment is initially estimated to be that of the last increment, a more accurate shelter dry-bulb temperature for the increment is computed using an iterative procedure.

Determination of Shelter Effective Temperature

After the shelter dry-bulb temperature for an increment has been computed, wet-bulb temperature is determined via the Carrier equation. Using a linear approximation, the effective temperature is calculated from:

$$ET = \frac{107.5\ T_{db} - 45.2\ T_{wb}}{T_{db} - T_{wb} + 62.3} \quad \text{for} \quad \begin{array}{l} 45°F \leq T_{db} \leq 110°F \\ 30°F \leq T_{wb} \leq 110°F \end{array}$$

where

T_{db} = dry-bulb temperature, °F

T_{wb} = wet-bulb temperature, °F

The psychrometric condition of the shelter atmosphere at the beginning of the next increment is then set equal to that at the end of the last increment and calculations for the next increment are begun. When one hour's calculations have been completed, the values for the last increment of the hour are printed out as the conditions at the end of the hour.

INTERPRETATION OF OUTPUT

The output of the SHEP program is a tabulation of the instantaneous values of the thermal loads affecting the shelter and the shelter psychrometric condition for the last increment of each hour of occupancy, see Figure 1. It must be remembered that these values are instantaneous and, while they reflect trends in the shelter system, interpolation between hourly values may be invalid. Also, hourly thermal loads determine the resultant hourly shelter temperature; however, the inverse process (i.e., compute loads from shelter temperature) is not valid. The 3600 computer system printer includes a procedure for rounding output to the format specified. Thus, the thermal loads are rounded in value to the nearest integer.

The air conditioning, boundary and condensation heat loads, when positive, represent energy lost from the shelter system; all other positive loads are energy additions. In the SHEP code, the assumptions associated with the calculations of the air conditioning, moisture condensation, and transmitted solar radiation loads generally lead to conservative estimates of these loads.

Maximum and minimum shelter temperatures and the hours of their occurrence are indicated. Average temperatures are computed for the entire occupancy period, for each full day of occupancy, and for specific intervals determined by the code user.

NOMINAL OCCUPANT ACTIVITY LEVEL 400 BTU/HR -OCCUPANT

VALUES ARE FOR LAST TIME INCREMENT OF EACH HOUR

LOADS (BTU/HR)

TIME HR	VENT RATE CFM/ OCC	DBT DEG F	WBT DEG F	ET DEG F	AIRCOND	BOUNDARY	CONDEN.	TRANS. SOLAR	METABOLIC SENSIBLE	METABOLIC LATENT	LIGHTING	EQUIPMENT
1	15.0	71.6	70.4	71.1	240042	-8124	0	0	281517	126522	6250	5000
2	15.0	72.1	70.4	71.4	243828	-35143	0	0	288206	120585	6250	5000
3	15.0	71.4	70.4	71.0	211179	-7494	0	0	281360	126678	6250	5000
4	15.0	72.1	70.5	71.4	234859	-44255	0	0	290442	118649	6250	5000
5	15.0	71.3	70.1	70.8	208811	-4419	0	0	280593	127302	6250	5000
6	15.0	72.4	70.5	71.6	214527	-47117	0	0	291142	118093	6250	5000
7	15.0	71.1	70.1	70.7	201581	3941	0	0	278501	129103	6250	5000
8	15.0	71.8	70.4	71.2	249394	-18241	0	0	284033	125348	6250	5000
9	15.0	72.3	70.5	71.5	268959	-22288	0	0	285035	123418	6250	5000
10	15.0	72.4	70.6	71.6	283330	5697	0	0	278060	129512	6250	5000
11	15.0	72.6	71.7	72.2	293154	22867	0	0	273733	132668	6250	5000
12	15.0	73.5	72.4	73.0	321451	34356	0	0	270817	135046	6250	5000
13	15.0	74.0	72.4	73.3	303665	35375	-3934	0	270558	135308	6250	5000
14	15.0	74.0	72.0	73.1	322330	52929	-11092	0	266069	139486	6250	5000
15	15.0	74.7	72.4	73.6	334872	56870	0	0	265056	140358	6250	5000
16	15.0	74.7	72.4	73.6	310299	83201	4888	0	258239	146342	6250	5000
17	15.0	74.5	72.1	73.5	327599	59815	0	0	264298	140971	6250	5000
18	15.0	74.3	72.3	73.4	329595	73790	0	0	260685	144169	6250	5000
19	15.0	74.4	72.3	73.5	329482	48923	0	0	267097	138600	6250	5000
20	15.0	73.1	72.2	72.7	302115	36330	17841	0	270315	135463	6250	5000
21	15.0	72.7	71.9	72.3	286673	9840	-6458	0	277020	129618	6250	5000
22	15.0	72.8	72.0	72.4	259851	10388	0	0	276882	129757	6250	5000
23	15.0	72.3	71.4	71.9	252150	-11170	0	0	282276	125301	6250	5000
24	15.0	71.9	71.2	71.6	247122	-6569	0	0	281129	126301	6250	5000

MAX. DRY-BULB TEMP. DURING OCCUPANCY 74.7 AT 15 HOURS AFTER BEGINNING OF OCCUPANCY

MIN. DRY-BULB TEMP. DURING OCCUPANCY 71.1 AT 7 HOURS AFTER BEGINNING OF OCCUPANCY

MAX. WET-BULB TEMP. DURING OCCUPANCY 72.4 AT 16 HOURS AFTER BEGINNING OF OCCUPANCY

MIN. WET-BULB TEMP. DURING OCCUPANCY 70.1 AT 5 HOURS AFTER BEGINNING OF OCCUPANCY

MAX EFFECTIVE TEMP. DURING OCCUPANCY 73.6 AT 16 HOURS AFTER BEGINNING OF OCCUPANCY

MIN EFFECTIVE TEMP. DURING OCCUPANCY 70.7 AT 7 HOURS AFTER BEGINNING OF OCCUPANCY

TIME-AVERAGE TEMPERATURE VALUES

		DBT	WBT	ET
FOR ENTIRE DURATION OF OCCUPANCY		72.8	71.4	72.2
FOR EACH DAY OF OCCUPANCY				
	DAY 1	72.8	71.4	72.2
FOR SPECIFIC INTERVALS	HRS			
	3- 6	71.8	70.4	71.2
	9- 15	73.3	71.7	72.6
	15- 24	73.5	72.0	72.9
	12- 18	74.2	72.3	73.3

Figure 1 Output of Sample Problem

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GENERAL AMERICAN RESEARCH DIVISION

FOREWORD

This user's manual was prepared by the General American Research Division of the General American Transportation Corporation for the Stanford Research Institute under Subcontract No. 11599(6300A-090). It explains in detail the procedure for using the computer code to calculate the response of a shelter to time-varying thermal loads and time-varying ventilation inlet psychrometric conditions. The code is based upon research performed between June 1963 and May 1968 on the Analysis of Shelter Ventilation Requirements which falls in the program area of OCD Work Unit 1215A.

The project was monitored by Mr. F. Allen (then at OCD) and Mr. D. Bettge of OCD, and Messrs. C. Grubb and J. Halsey of SRI.

The authors wish to thank Messrs. H. Moy, M. Lokmanhekim, D. Liddell, and A. Kapil of GARD, Dr. J. Buchanan of OCD, Mr. P. Achenbach and Dr. T. Kusuda of the National Bureau of Standards, Mr. W. Spiegel, Consulting Engineer, and Messrs. F. Hughes-Caley and T. Hori of SRI for their comments and criticism. The valuable cooperation of the personnel at the OCD computer facility in Olney, Maryland and the Control Data Corporation computer facility in Chicago, Illinois is acknowledged.

It should be noted that the version of the SHEP code presented in this report (Mod. 3) has been superseded by a new modification (Mod. 6). This new code employs a slightly different sequence of calculation to decrease calculation time.

ABSTRACT

The Shelter Environmental Prediction (SHEP) Computer Code, Modification 3, calculates the response of a shelter to time-varying thermal loads and time-varying ventilation inlet psychrometric conditions. The code accommodates solar radiation, boundary surface heat transfer, moisture condensation on the boundaries, equipment and lighting loads, and air conditioning. The manual explains the various features of the code, presents the input and output formats, gives representative input data values, and includes an application of the code to a typical shelter structure.

The required inputs to the code and the outputs obtainable from it are given below:

Inputs

1. Ventilation rate
2. Inlet psychrometric conditions
3. Shelter geometric characteristics
4. Shelter thermal characteristics
5. Shelter latitude, longitude and altitude
6. Period of occupancy

1. Hourly temperatures
2. Hourly air conditioning load
3. Hourly boundary heat transfer
4. Hourly metabolic loads
5. Average temperatures (dry-bulb, wet-bulb, effective) for the entire occupancy or specified hours of occupancy
6. Maximum and minimum temperatures (dry-bulb, wet-bulb, effective) during the occupancy.

The code is written in FORTRAN IV specifically for the CDC 3600 computer system and consists of approximately 780 cards. It requires a memory bank of at least 65^k words (each word of 48 bits) for the code and the accompanying matrices. For the CDC 3600 and for a problem comparable to the sample problem presented in the text, the compilation time is approximately 1 min., 45 sec. and the execution time approximately 1 sec. for each hour of shelter occupancy.

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SECTION 1

INTRODUCTION

The Shelter Environmental Prediction (SHEP) code will calculate the environmental response of a shelter, or any large structure, to time-varying thermal loads and ventilation inlet psychrometric conditions. Shelter conditions computed by finite difference methods define the history of the shelter environment during occupancy.

The SHEP code accommodates solar radiation, boundary surface heat transfer, moisture evaporation or condensation on the boundaries, equipment and lighting loads, and air conditioning (derivations of the corresponding equations are given in the Appendices). Little technical knowledge of mass or energy transfer is required by a user of the SHEP code. Information that must be supplied includes shelter physical, thermal and geometrical characteristics, occupancy levels and durations, and hourly inlet conditions. The amount of required data is admittedly large, but is necessary so that the SHEP code will remain applicable to a wide variety of shelters.

The shelter model used in the code is based upon the assumptions that:

1. Air within the shelter and ventilation air is completely and instantaneously mixed, so that one psychrometric condition will completely specify the shelter environment;
2. Moisture condensation and evaporation is filmwise with the convective heat transfer coefficients constant over each boundary surface, but variable from boundary to boundary.
3. Radiative energy transfer between the shelter boundaries is neglected.

4. Shelter exhaust air is at the psychrometric condition of the shelter atmosphere; and

5. Thermal and physical properties of the air and of the structural materials are not temperature-dependent.

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SECTION 2

FEATURES OF THE PROGRAM

The shelter model used by the SHEP code is an accurate description of the actual shelter under analysis because of the methods which have been formulated in the code to handle the thermal processes which affect the shelter environment. These processes include:

1. solar radiation,
2. air conditioning,
3. moisture evaporation and condensation,
4. time-varying inlet conditions, and
5. boundary heat transfer.

It has been found that during extreme hot weather, many actual shelters respond as if they had adiabatic boundaries. Thus, the code has the ability of analyzing a shelter with adiabatic or non-adiabatic shelter boundaries.

The complexity of the code has necessitated the printout of diagnostic error messages. These are included as a safeguard against using illegal variable values, or exceeding the inherent limits of the equations comprising the code.

2.1 Shelter Boundaries

An actual shelter is bounded by walls, floor and ceiling, composed of several different kinds of materials (e.g., cement, glass, metal, etc.) and these can be at any orientation (slope and azimuth). In addition, the exterior boundary surface may be exposed to various media (e.g., air, soil, etc.). Therefore, a "boundary" is defined as a plane or approximately plane curved surface* of the shelter enclosure consisting of a homogeneous inner layer and

*See Appendix E.

successive homogeneous layers exposed to one external medium. If windows are included in one wall of the shelter and this wall is partially underground, then this wall consists of three boundaries (see Figure 2-1). A shelter volume may be defined by up to 20 boundaries. A curvilinear boundary should be considered plane, with its orientation that of the plane tangent to the boundary at its midpoint (see Appendix E).

An implicit finite-difference approach based upon a one-dimensional node array is used to compute temperature distribution across a boundary, with each boundary spanned by up to 40 nodal points. A boundary may consist of up to 5 layers, each having distinct thermal properties and nodal-point spacings. An air space within a boundary and a soil media adjacent to a belowgrade boundary are considered as layers of the respective boundaries. Shelter tests have shown that 10 feet from the exterior boundary surface, the soil temperature is invariant. Thus the soil can be considered as a layer 10 feet thick whose exterior surface is at the undisturbed soil temperature.

Nodal point spacing in a typical boundary consisting of 4 layers is shown in Figure 2-2. Each layer is divided into slab Δx_i thick and a nodal point is placed at the center of each slab. The innermost and outermost points are $\Delta x_i/2$ from the next inner nodal point and are placed at the surface of the layer (see Appendix C). It should be noted that there is a nodal point at each surface and at each interface, and that the nodal point numbering is continuous.

The number of nodal points in each layer is

$$n_k = \frac{\text{layer thickness}}{\Delta x_k} + 1$$

which includes the node on the inner surface of the layer. The number of

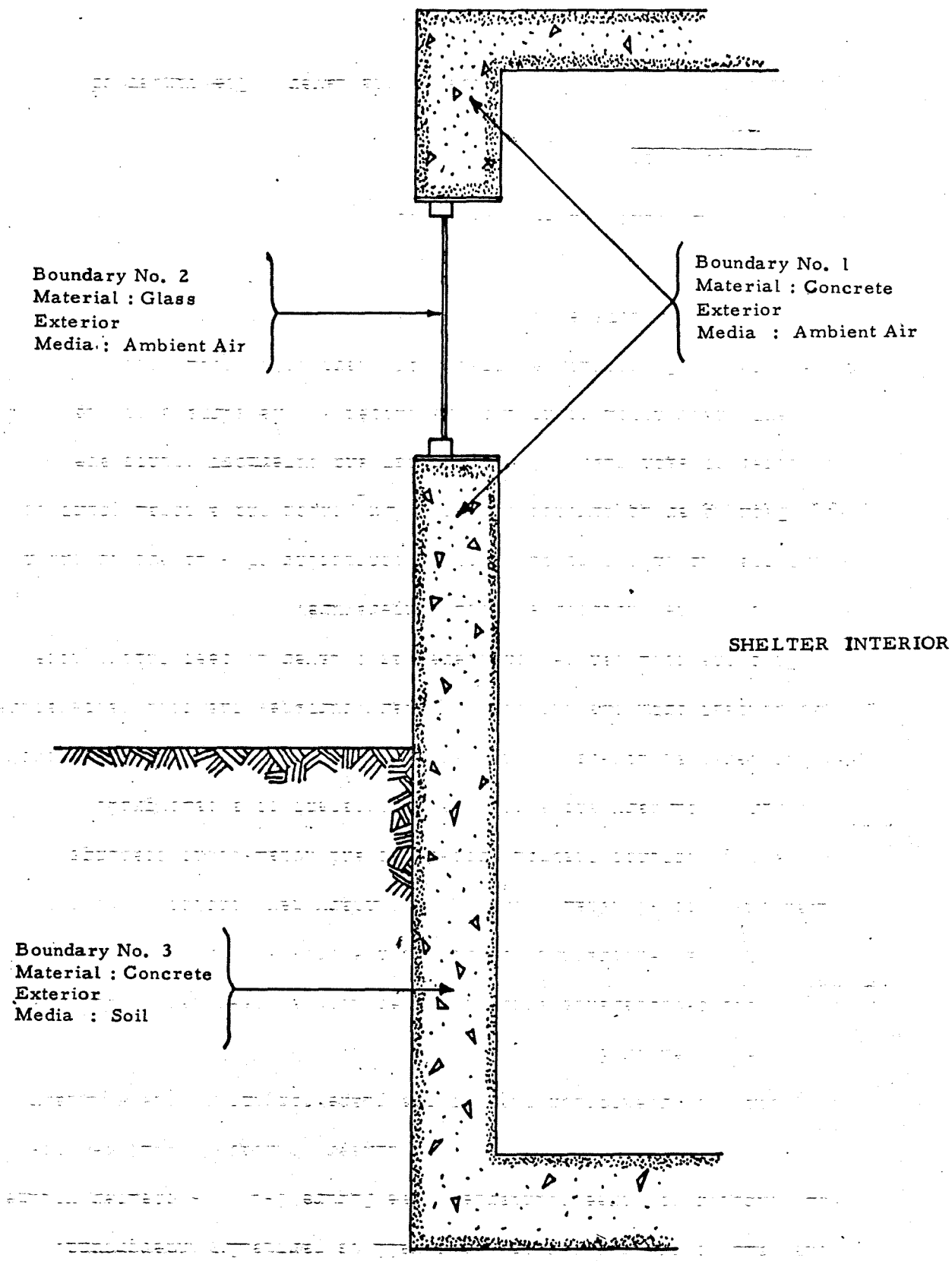


Figure 2-1 A Typical Shelter Wall Consisting of Three Boundaries

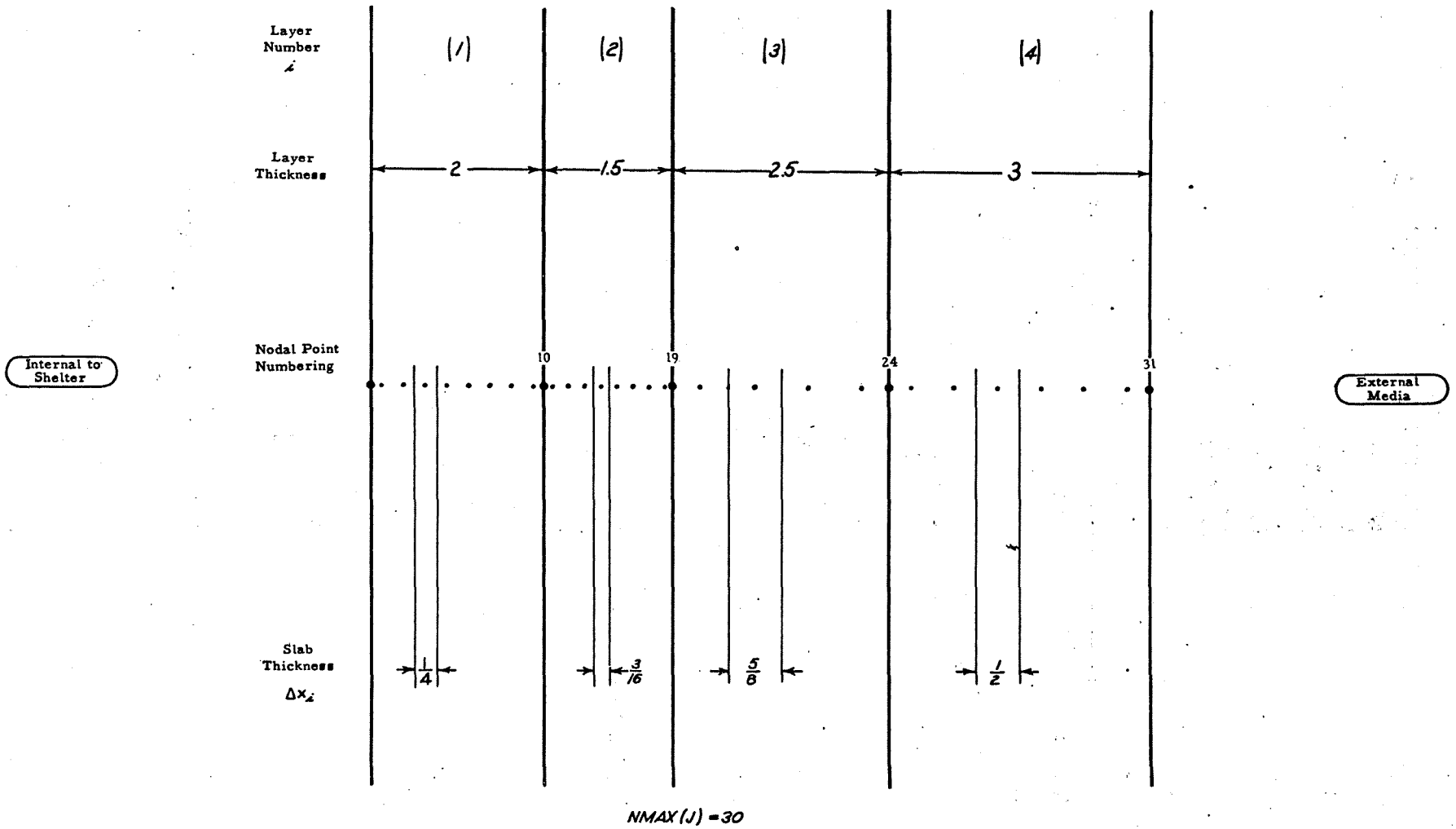


Figure 2-2 Typical Nodal Point Arrangement in a Four-layered Boundary

nodal points in a wall excluding the outermost point is $NMAX_j$ and must be supplied by the programmer. It is given by

$$NMAX_j = \sum_{layers} n_k$$

and the total number of nodal points is

$$N_j = NMAX_j + 1$$

Spacing between nodal points should vary inversely with conductivity. Suggested spacing in soil is one-half to one foot; in structural materials, one inch.

The nodal point approach to the temperature profile across the boundary permits an implicit representation of the temperature through the boundary via the simultaneous linear equations:

$$\begin{aligned}
a_{11}T_1 + a_{12}T_2 \qquad\qquad\qquad\qquad\qquad\qquad\qquad\qquad\qquad\qquad &= b_1 \\
a_{21}T_1 + a_{22}T_2 + a_{23}T_3 \qquad\qquad\qquad\qquad\qquad\qquad\qquad\qquad &= b_2 \\
a_{32}T_2 + a_{33}T_3 + a_{34}T_4 \qquad\qquad\qquad\qquad\qquad\qquad\qquad\qquad &= b_3 \\
\cdots\cdots\cdots\cdots \qquad\qquad\qquad\qquad\qquad\qquad\qquad\qquad\qquad\qquad &\cdot\cdot \\
\cdots\cdots\cdots\cdots\cdots\cdots \qquad\qquad\qquad\qquad\qquad\qquad\qquad\qquad &\cdot\cdot \\
a_{n-1,n-2}T_{n-2} + a_{n-1,n-1}T_{n-1} + a_{n-1,n}T_n \qquad\qquad\qquad\qquad &= b_{n-1} \\
a_{n,n-1}T_{n-1} + a_{n,n}T_n \qquad\qquad\qquad\qquad\qquad\qquad\qquad\qquad\qquad &= b_n
\end{aligned}$$

obtained by applying an energy balance at each of n nodes. The a's are the coefficients of the temperatures at each node and the b's are the heat storage terms, which are time-dependent. In matrix form, the equations become:

$$[A]\ [T] = [B]$$

These equations may be solved for the nodal temperatures:

$$[T] = [A]^{-1} [B]$$

and the heat transfer through a non-adiabatic boundary due to conduction may be computed based on the interior boundary surface temperatures. In addition, for non-adiabatic boundaries, heat loss due to moisture condensation or evaporation on the interior boundary surfaces is computed. The derivations of the equations for determining the $[A]$ and $[B]$ coefficients, and those for heat transfer due to condensation, are given in Appendix C. This implicit procedure does not have the stability considerations associated with the explicit method. Thus, longer time intervals can be utilized at each finite difference increment. If the boundaries are considered adiabatic, heat transfer both through the boundary and due to condensation or evaporation on the surface are considered zero.

2.2 Solar Radiation

If a surface is exposed to ambient air, it will normally be exposed to direct, diffuse and/or reflected solar radiation. If the surface is a shelter boundary, the incident radiation will serve to raise the shelter temperature in two ways. First, incident radiation will be partially absorbed by the boundary, thus raising its temperature and, in time, the temperature of the shelter. Second, radiation transmitted through the boundary will be incident on interior surfaces, similarly raising their temperatures and that of the shelter atmosphere.

SHEP makes several simplifying assumptions in treating the effects of solar radiation. One of these is that all reflected radiation, both that which falls onto the shelter surfaces from surrounding objects and that which

is reflected from the shelter surfaces, is neglected. Also, radiation transmitted through a boundary is considered an instantaneous thermal load inside the shelter, similar to the lighting and equipment loads.

All calculations involving solar radiation are done using solar time, which differs slightly from Civil Time. The relation may be expressed as

$$\text{Solar Time} = \text{Civil Time} + \text{Equation of Time} + \Delta_{long}$$

Civil Time is that time assigned to a zone covering approximately 15° of longitude; it is the same as Standard Time. Since local time actually does not remain constant within each 15° zone, but varies by four minutes for each degree within the zone, a correction factor, Δ_{long}, takes this into account. The Equation of Time is the difference between mean solar time and apparent solar time and is given as the (12^h-Ephemeris Transit). See Reference 1. Solar time is computed in the program knowing the time of the start of occupancy, the longitude of the shelter, and the first day of occupancy.

Variation of the Equation of Time is shown in Figures 2-3 and the values used in the program are listed in Table I. The daily values of the Equation of Time change slightly from year to year, but the actual values remain within 0.3 min. of those listed (see Reference 2).

Solar radiation intensity is computed once each time increment for each exposed wall. (See Appendix B.) Although radiation will penetrate into a surface a certain distance before being absorbed, the SHEP code assumes this absorption phenomenon is a surface effect. Also, even though the transmittance of the boundary material may vary with incident wavelength, only a total transmittance value is used in the code.

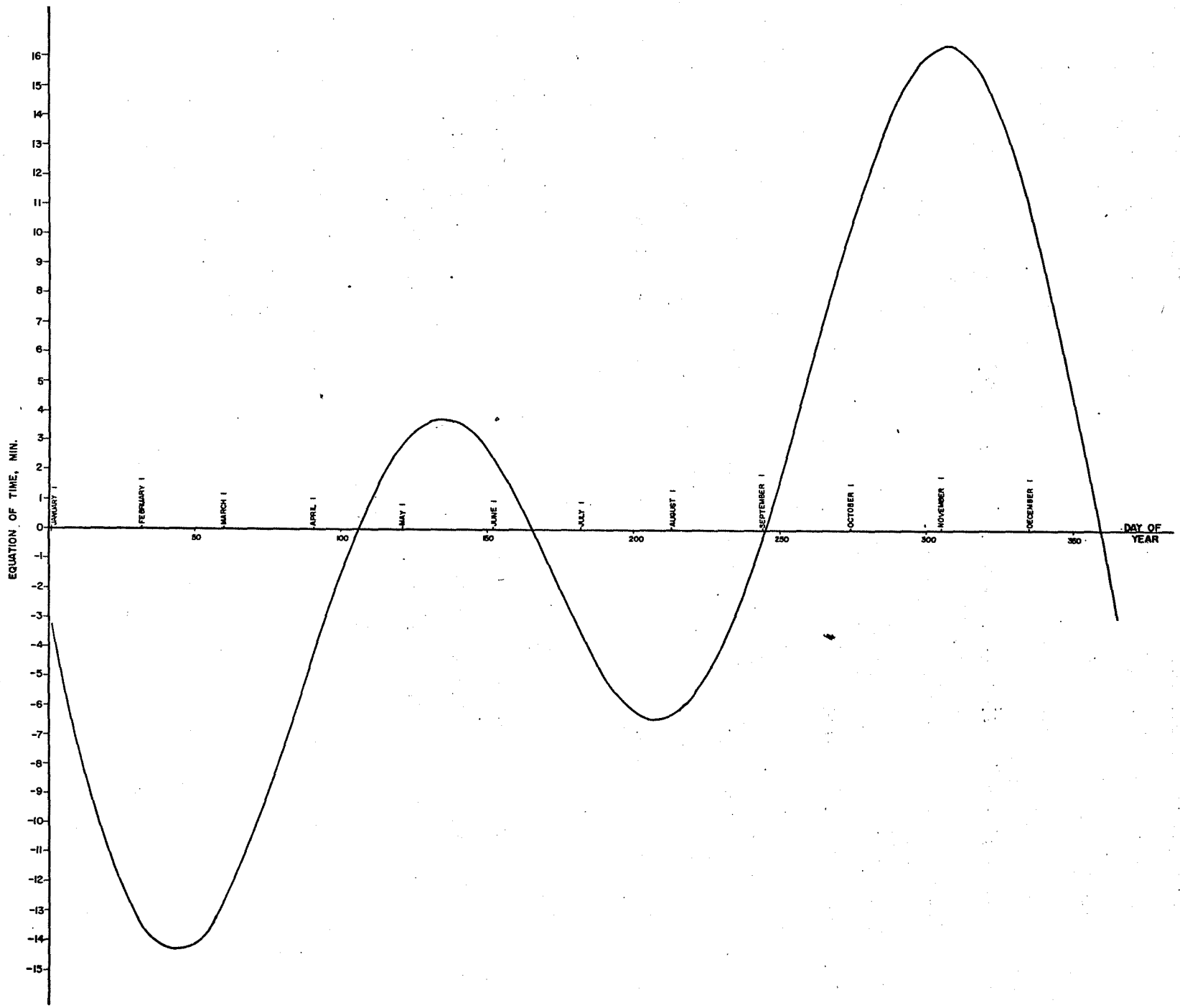


Figure 2-3 Equation of Time

TABLE I EQUATION OF TIME VALUES AS A FUNCTION OF DAY OF YEAR

DAY	VALUE*	DAY	VALUE	DAY	VALUE	DAY	VALUE	DAY	VALUE	DAY	VALUE	DAY	VALUE	DAY	VALUE	DAY	VALUE	DAY	VALUE	DAY	VALUE	DAY	VALUE
1	-.05	32	-.23	63	-.20	94	-.05	125	.05	156	.03	186	-.07	216	-.10	246	.00	276	.18	306	.27	336	.18
2	-.06	33	-.23	64	-.20	95	-.05	126	.06	157	.03	187	-.08	217	-.10	247	.01	277	.18	307	.27	337	.17
3	-.07	34	-.23	65	-.19	96	-.04	127	.06	158	.02	188	-.08	218	-.10	248	.02	278	.19	308	.27	338	.17
4	-.08	35	-.23	66	-.19	97	-.04	128	.06	159	.02	189	-.08	219	-.10	249	.02	279	.19	309	.27	339	.16
5	-.09	36	-.23	67	-.18	98	-.04	129	.06	160	.02	190	-.08	220	-.09	250	.03	280	.20	310	.27	340	.15
6	-.09	37	-.24	68	-.18	99	-.03	130	.06	161	.01	191	-.09	221	-.09	251	.03	281	.20	311	.27	341	.14
7	-.10	38	-.24	69	-.18	100	-.03	131	.06	162	.01	192	-.09	222	-.09	252	.04	282	.21	312	.27	342	.14
8	-.11	39	-.24	70	-.17	101	-.02	132	.06	163	.01	193	-.09	223	-.09	253	.04	283	.21	313	.27	343	.13
9	-.12	40	-.24	71	-.17	102	-.02	133	.06	164	.00	194	-.09	224	-.08	254	.05	284	.22	314	.27	344	.12
10	-.12	41	-.24	72	-.16	103	-.01	134	.06	165	.00	195	-.09	225	-.08	255	.06	285	.22	315	.27	345	.12
11	-.13	42	-.24	73	-.16	104	-.01	135	.06	166	.00	196	-.10	226	-.08	256	.06	286	.22	316	.26	346	.11
12	-.14	43	-.24	74	-.15	105	.00	136	.06	167	-.01	197	-.10	227	-.08	257	.07	287	.23	317	.26	347	.10
13	-.14	44	-.24	75	-.15	106	.00	137	.06	168	-.01	198	-.10	228	-.07	258	.07	288	.23	318	.26	348	.09
14	-.15	45	-.24	76	-.14	107	.00	138	.06	169	-.01	199	-.10	229	-.07	259	.08	289	.24	319	.26	349	.09
15	-.15	46	-.24	77	-.14	108	.01	139	.06	170	-.02	200	-.10	230	-.07	260	.09	290	.24	320	.26	350	.08
16	-.16	47	-.24	78	-.14	109	.01	140	.06	171	-.02	201	-.10	231	-.06	261	.09	291	.24	321	.25	351	.07
17	-.17	48	-.24	79	-.13	110	.01	141	.06	172	-.02	202	-.10	232	-.06	262	.10	292	.25	322	.25	352	.06
18	-.17	49	-.24	80	-.13	111	.02	142	.06	173	-.03	203	-.11	233	-.06	263	.10	293	.25	323	.24	353	.05
19	-.18	50	-.24	81	-.12	112	.02	143	.06	174	-.03	204	-.11	234	-.05	264	.11	294	.25	324	.24	354	.05
20	-.18	51	-.23	82	-.12	113	.02	144	.06	175	-.03	205	-.11	235	-.05	265	.12	295	.26	325	.24	355	.04
21	-.19	52	-.23	83	-.11	114	.03	145	.05	176	-.04	206	-.11	236	-.04	266	.12	296	.26	326	.23	356	.03
22	-.19	53	-.23	84	-.11	115	.03	146	.05	177	-.04	207	-.11	237	-.04	267	.13	297	.26	327	.23	357	.02
23	-.19	54	-.23	85	-.10	116	.03	147	.05	178	-.04	208	-.11	238	-.03	268	.13	298	.26	328	.22	358	.01
24	-.20	55	-.23	86	-.10	117	.04	148	.05	179	-.05	209	-.11	239	-.03	269	.14	299	.26	329	.22	359	.00
25	-.20	56	-.22	87	-.09	118	.04	149	.05	180	-.05	210	-.11	240	-.02	270	.15	300	.27	330	.21	360	.00
26	-.21	57	-.22	88	-.09	119	.04	150	.04	181	-.06	211	-.11	241	-.02	271	.15	301	.27	331	.21	361	-.01
27	-.21	58	-.22	89	-.08	120	.04	151	.04	182	-.06	212	-.11	242	-.02	272	.16	302	.27	332	.20	362	-.02
28	-.21	59	-.21	90	-.08	121	.05	152	.04	183	-.06	213	-.10	243	-.01	273	.16	303	.27	333	.20	363	-.03
29	-.22	60	-.21	91	-.07	122	.05	153	.04	184	-.07	214	-.10	244	.00	274	.17	304	.27	334	.19	364	-.04
30	-.22	61	-.21	92	-.06	123	.05	154	.04	185	-.07	215	-.10	245	.00	275	.17	305	.27	335	.19	365	-.04
31	-.22	62	-.20	93	-.06	124	.05	155	.03														

* Hr

2.3 Air Conditioning

In a typical air conditioning unit, warm air passes over cooling coils, thereby lowering its dry-bulb temperature through convective heat exchange and lowering its moisture content through condensation. The temperature of the coils is not constant, but varies as a function of load. Typically, all the air passing through the air conditioner does not experience these heat and mass transfer processes due to flow turbulence.

The method the SHEP code utilizes to calculate the air conditioning load assumes that the temperature of the coils and the percentage of air unaffected by passing through the unit do not vary with the cooling load. An "effective coil surface temperature" is assumed as the design temperature of the coils; and a "coil bypass factor" is the design value of the percentage of air unaffected by the cooling units. If these two parameters are both assumed constant, the air conditioning performance of an actual unit can be estimated reasonably well. See Appendix F, which is based upon Reference 3.

A typical air conditioning system for a shelter may be represented by the schematic diagram of Figure 2-4; the various psychrometric states of the air in the system are indicated in the accompanying psychrometric chart. Note that "return air bypass" refers to air not passing through air conditioning unit; "coil bypass factor" is a characteristic of the unit itself. Outside air at state point 1 enters the system and is adiabatically mixed with return air at the shelter condition, S, to create state point 2. A portion of this air passes through the air conditioning unit, exiting with a lower dry-bulb temperature and a low humidity ratio, state point 3, and is then adiabatically mixed with the unconditioned air to give state point 4. Air at this condition is the inlet air to the shelter which is then used to compute the new shelter condition, S'.

The ventilation rates of outside air entering the system, of air passing through the air conditioning unit, and of air entering the shelter must all be specified by the code user. Therefore, the mixing processes can be altered, or even eliminated, by varying the various ventilation rates.

Air conditioning removes both sensible and latent energy. This energy removal, ΔQ, is given by

$$\Delta Q = c_p \dot{m} \Delta T + h_{fg} \dot{m} \Delta W$$

where

c_p = specific heat of air $\approx$ 0.24 Btu/lb °F

$\dot{m}$ = mass flow rate of dry air through the air conditioning unit, lb/hr

ΔT = temperature difference across the unit, °F

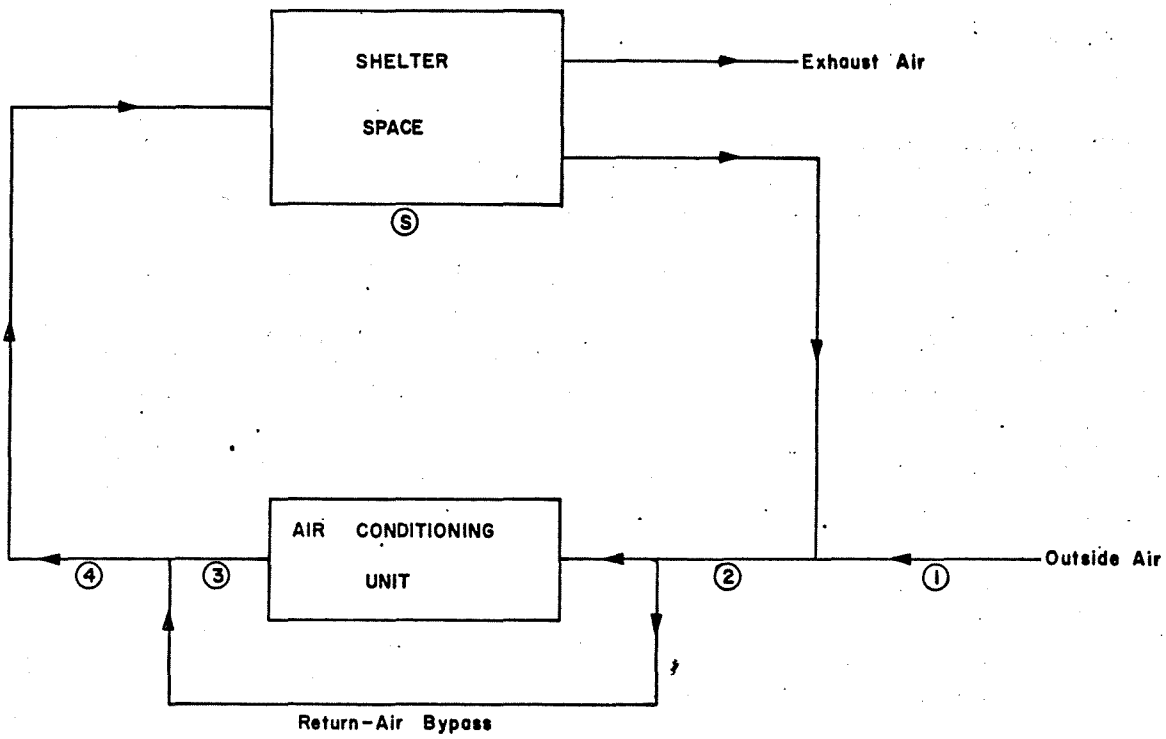
h_{fg} = heat of condensation of water vapor, Btu/lb water

ΔW = humidity ratio difference across the unit, lb water/lb dry air

2.4 Moisture Condensation

Whenever the vapor pressure at the interior surface of a boundary is lower than the vapor pressure of the shelter atmosphere, moisture will migrate to and condense on the surface, thereby removing energy from the shelter environment. If, at another time, the vapor pressure at the boundary surface is higher than the vapor pressure of the shelter air, the process will be reversed and condensed water on the surface will re-evaporate and migrate into the shelter atmosphere.

If sufficient moisture condenses, it will run down the walls and accumulate on the floor of the shelter. Since the SHEP code assumes that condensation occurs in an even film on an interior surface, the effect of gravity is neglected.



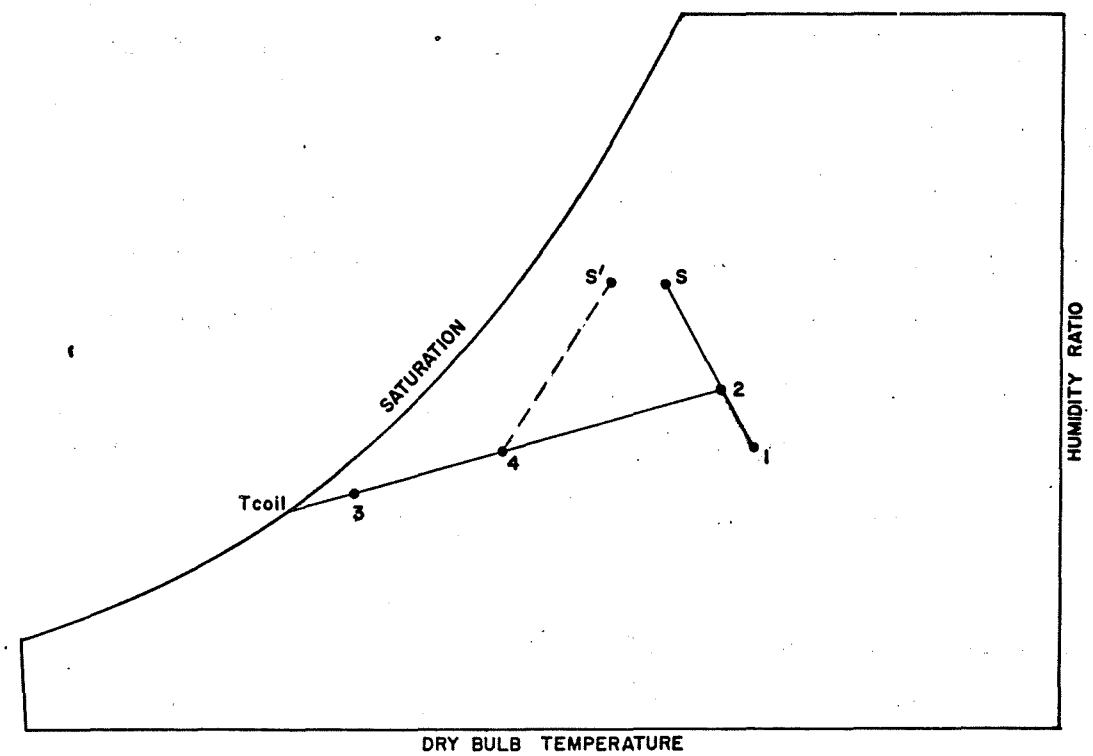


Figure 2-4 Schematic Diagram of a Shelter Air-Conditioning System and the Corresponding Processes on a Skeleton Psychrometric Chart

In the code, the vapor pressure at the boundary surface is assumed to be the saturation pressure of water vapor at the temperature of the boundary surface. Values of saturation pressures as a function of dry-bulb temperature (see Table II) are a part of the standard input data. Only the range of temperatures from 50°F to 120°F are considered, since metabolic relations used in the SHEP code are invalid outside of this range.

2.5 Metabolic Loads

The metabolic expressions of Houghten[5*] are adopted in this study since they reflect effects of relative humidity in the shelter. They are given by

$$Q_{sensible} = -0.06875(T_{db})^2 + 1.625(T_{db}) + 523.0 \qquad \text{for } T_{db} \geq 50°F$$

$$Q_{total} = \begin{cases} -1.482\ (ET) + 514.0 & \text{for } 50°F \leq ET \leq 87°F \\ -1.508\ (ET)^2 + 259.7\ (ET) - 10795.2 & \text{for } 87°F < ET \leq 102°F \\ 0.0\ \ (\text{assumed}) & \text{for } ET > 102°F \end{cases}$$

with $Q_{latent} = Q_{total} - Q_{sensible}$, assuming that the body is in thermal equilibrium with the shelter environment, and hence, neglecting the heat storage term.

2.6 Auxiliary Loads

Lighting and equipment loads are introduced as inputs and may be time-varying (on an hourly basis).

2.7 Varying Inlet Conditions

The psychrometric condition of the shelter atmosphere and of the entering ventilation air are considered by the code as a function of dry-bulb temperature and relative humidity.

Certain factors which affect the shelter atmosphere normally vary with time; ambient temperature and relative humidity are chief among these. Other factors which may change during occupancy are:

*Superscripts refer to ~~references, p. 7~~-1.

TABLE II

SATURATION PRESSURE, P_S, AS A FUNCTION OF DRY-BULB TEMPERATURE, T_{db}

T_{db}*	P_S**	T_{db}	P_S	T_{db}	P_S	T_{db}	P_S	T_{db}	P_S
50	25.648	64	42.494	78	68.357	92	107.021	106	163.368
51	26.620	65	44.006	79	70.646	93	110.390	107	168.235
52	27.622	66	45.562	80	72.994	94	113.846	108	173.218
53	28.656	67	47.174	81	75.413	95	117.403	109	178.330
54	29.724	68	48.816	82	77.904	96	121.061	110	183.571
55	30.830	69	50.530	83	80.467	97	124.819	111	188.942
56	31.968	70	52.286	84	83.102	98	128.664	112	194.458
57	33.149	71	54.086	85	85.810	99	132.624	113	200.102
58	34.358	72	55.958	86	88.589	100	136.685	114	205.891
59	35.611	73	57.873	87	91.454	101	140.846	115	211.809
60	36.907	74	59.846	88	94.406	102	145.123	116	217.872
61	38.232	75	61.891	89	97.430	103	149.501	117	224.107
62	39.614	76	63.979	90	100.541	104	154.008	118	230.486
63	41.040	77	66.139	91	103.738	105	158.630	119	237.010
								120	243.706

*T_{db}: °F

**P_S: lb/ft^2

1. the number of occupants,

2. the ventilation rate, and

3. the lighting and equipment loads.

In the code, these factors may have different values for each hour of occupancy.

2.8 Error Messages

Since many of the relations used in SHEP are valid only over certain ranges, limits have been placed on the values of certain input data and of certain computed variables. If these limits are exceeded, diagnostic error messages are printed, stating what variable is in error and what value it has at the time it exceeded its limit. If an input variable has an illegal value, this will be indicated and the run will terminate; if a computed variable is invalid, this fact will be printed and the run will continue. A third type of diagnostic message is generated through machine error; for instance, if an index has overrun its bound.

A list of the error messages is indicated in Table III. These error messages are incorporated into the SHEP code and are in addition to the compilation and execution diagnostic routines of the machine.

2.9 Determination of Shelter Dry-Bulb Temperature

All thermal loads and enthalpies are computed at the begining of a time increment based upon an estimate of what the shelter dry-bulb temperature will be. Then the net amount of energy added to the shelter system during that increment is calculated. With this value, the shelter dry-bulb temperature can be computed by equation 20 of Appendix A. Since the shelter dry-bulb temperature of the increment is initially estimated to be that of the last increment, an iteration procedure is used to permit each calculated temperature

TABLE III

ERROR MESSAGES

1. Input Variables Illegal

   A. "Inclination Angle XI (___) is ___. This value must be 90° or less."

   B. "The latitude of the shelter is greater than the program can handle for this day of the year."

2. Calculated Variables Illegal

   A. "R during hour ___ is ___, which is less than 1.0. Therefore, the latent metabolic energy has been reduced."

   B. "Shelter effective temperature during hour ___ is ___ which exceeds the limits on the metabolic relations."

   C. "Shelter dry-bulb temperature during hour ___ is ___ which exceeds the limits on the metabolic relations."

   D. "The relative humidity in the shelter has exceeded saturation."

3. Procedural Errors

   A. "The limits on laymax or nmax of wall ___ have been exceeded."

   B. "The number of shelter boundaries, NW, has been exceeded."

   C. "The number of iterations for an increment has exceeded the value of IDATA(3)."

   D. "The number of increments in an hour exceeds the value of IDATA(5)."

   E. "The hour numbers are not indexing properly."

   F. "The hour number has exceeded the length of occupancy."

to be used as a new estimate to compute a more accurate shelter dry-bulb temperature.

The number of iterations for each increment is a function of the accuracy of the initial estimate. If the dry-bulb temperatures computed on two successive iterations are less than 1°F apart, the last temperature computed is assumed to be the value for the increment and the iteration procedure is curtailed. Otherwise, the procedure is continued until the number of iterations reaches the value of IDATA(3), (see Section 3).

2.10 Determination of Shelter Effective Temperature

After the shelter dry-bulb temperature for an increment has been computed, wet-bulb temperature is determined via the Carrier equation (equation 41 of Appendix A). Using a linear approximation to the nomogram of Reference 4, the effective temperature is calculated from:

$$ET = \frac{107.5\ T_{db} - 45.2\ T_{wb}}{T_{db} - T_{wb} + 62.3} \quad \text{for} \begin{cases} 45°F \leq T_{db} \leq 110°F \\ 30°F \leq T_{wb} \leq 110°F \end{cases}$$

where T_{db} = dry-bulb temperature, °F

T_{wb} = wet-bulb temperature, °F

The psychrometric condition of the shelter atmosphere at the beginning of the next increment is then set equal to that at the end of the last increment and calculations for the next increment are begun. When one hour's calculations have been completed, the values for the last increment of the hour are printed out as the conditions at the end of the hour.

SECTION 3

INPUT DATA

Input data consist of physical constants, hourly occupancy constants, geometrical and thermal characteristics of the shelter, and initial conditions. The input variables and their definitions are given below; where units are not indicated, the value is dimensionless.

ALAT -Latitude of the shelter, degrees. The limits on the range of ALAT are a function of the time of the year, see Figure 3-1.

ALONG -Longitude of the shelter, degrees. Only values in the range 0° to 180° W are allowed.

ALT -Altitude of the shelter, feet.

AREA(j) -Area of boundary j, ft^2.

ASOIL(j) -Control constant determining the media exterior to the outer surface of boundary j.

$$ASOIL(j) = \begin{cases} -1 & \text{ambient air} \\ 0 & \text{interior air} \\ 1 & \text{soil} \end{cases}$$

AZ(j) -Azimuth angle of boundary j. AZ(j) is measured in a clockwise direction from north to the outward-pointing normal to the boundary. Values between 0° and 360° are permitted. For a boundary facing east, AZ(j) = 90°; if it faces west, AZ(j) = 270°.

BF -Cooling coil bypass factor of the air conditioning unit. It is defined as

$$BF = \frac{t_f - t_e}{t_d - t_e}$$

where t_f = air temperature leaving the coil, °F

t_e = coil effective surface temperature, °F (TCOIL)

t_d = air temperature entering the coil, °F

The suggested value is 0.15.

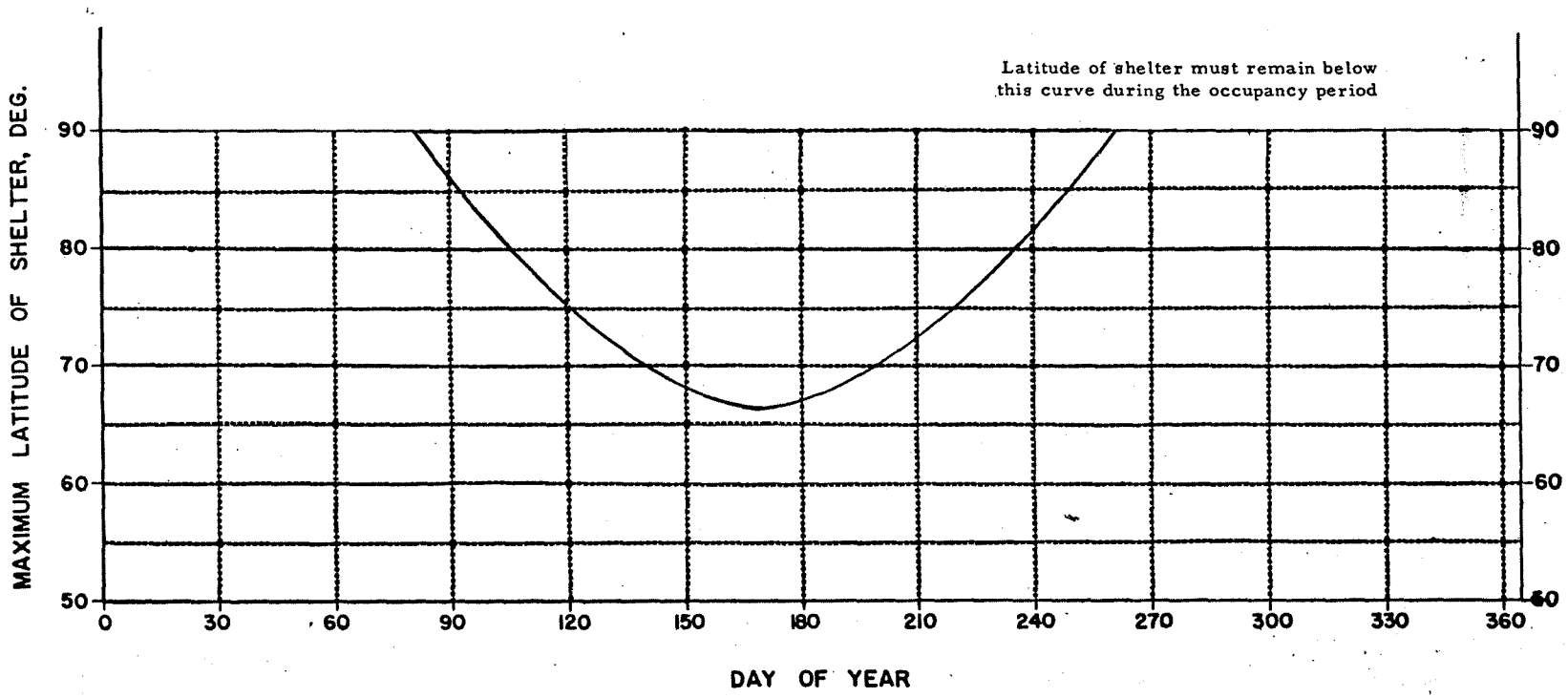


Figure 3-1 Allowable Values of the Shelter Latitude, ALAT

CFMIN -Total ventilation rate through air conditioner, cfm.

CON(k,j) -Thermal conductivity of material of layer k of boundary j. Btu/hr-ft-°F.

CP(k,j) -Specific heat of material of layer k of boundary j, Btu/lb-°F.

D -Day number of the start of occupancy. Values in the range of 1-365 are allowed, e.g., for January 1, D = 1.

DP(k,j) -Thickness of layer k of boundary j, feet.

DT -Time increment of shelter history used in finite-difference equations, hrs. $0.00 < DT \leq 0.500$ hours, DT = 0.167 is suggested.

DX(k,j) -Nodal point spacing of layer k of boundary j, feet.

EQTIM(i) -Equation of Time for day i, hours. See Table I.

F1 -Total ventilation rate entering shelter, cfm.

F2 -Total ventilation rate of outside air entering shelter system, cfm.

GG -Equivalent interior length of shelter, feet. Equivalent dimensions are those of a parallelepiped approximating the shelter under analysis.

HH -Equivalent interior height of shelter, feet.

HI(j) -Interior film heat transfer coefficient of boundary j, Btu/hr-ft^2-°F.

HO(j) -Exterior film heat transfer coefficient of boundary j, Btu/hr-ft^2-°F.

HRS -Total number of continuous hours of shelter occupancy.

IDATA(1) -Sets initial boundary temperatures

$$IDATA(1) = \begin{cases} 1 & \text{- all boundary nodes have different temperatures} \\ 0 & \text{- all boundary nodes have same temperature} \end{cases}$$

IDATA(2) -Reference constant; IDATA(2) = 0 is suggested.

IDATA(3) -Number of iterations for computing incremental shelter dry-bulb temperature. IDATA(3) = 4 is suggested.

IDATA(4) -Number of shelters to be analyzed in the computer run.

IDATA(5) -1 hour/DT, rounded to the nearest integer.

IDATA(6) -Sets type of boundary.

$$\text{IDATA(6)} = \begin{cases} 1 \text{ - for all non-adiabatic boundaries} \\ 0 \text{ - for all adiabatic boundaries} \end{cases}$$

IDATA(7) -Determines presence of air conditioning.

$$\text{IDATA(7)} = \begin{cases} 0 \text{ - no air conditioning} \\ 1 \text{ - air conditioning is present} \end{cases}$$

IDATA(8) -Reference constant, IDATA(8) = 0 is suggested.

IDATA(9) -Reference constant, IDATA(9) = 0 is suggested.

IDATA(10) -Sets atmospheric condition for solar radiation.

$$\text{IDATA(10)} = \begin{cases} 0 \text{ - for clear atmosphere} \\ 1 \text{ - for industrial atmosphere} \end{cases}$$

IDATA(11) -Establishes format of printout.

$$\text{IDATA(11)} = \begin{cases} 1 \text{ - Standard output format} \\ 0 \text{ - Only maximum, minimum and average temperatures are printed} \end{cases}$$

IDATA(12) -Establishes variability of occupancy values.

$$\text{IDATA(12)} = \begin{cases} 0 \text{ - P, F1, CFMIN, QLITE, QEQUIP change for each hour.} \\ 1 \text{ - These variables are held constant for entire occupancy.} \end{cases}$$

IDATA(13) -Establishes variability of inlet values.

$$\text{IDATA(13)} = \begin{cases} 1 \text{ - Inlet conditions held constant for entire occupancy} \\ 0 \text{ - These variables change for every hour of occupancy.} \end{cases}$$

INT(m) -Hour limits of the intervals for which average temperatures are desired, e.g., for average dry-bulb temperatures from hour number 3 to hour number 9 of occupancy, then INT(1) = 3, INT(2) = 9. INT(m), where m is an odd integer, $1 \leq m \leq 59$ determines the start of an interval; and INT(m+1) determines the end of the interval.

LAYMAX(j) -Number of layers in boundary j. Soil back of a boundary or an air space within a boundary is considered a layer of the boundary. Value must be 5 or less.

LST(1) -Local Standard Time at beginning of occupancy; defined in terms of military time (0-23 hrs).

NMAX(j) - Number of nodal points in boundary j. If a boundry is soil-backed, the nodal points extend into and through the soil, up to a suggested distance of 10 feet. Integral values up to 39 are permitted. The outermost nodal point is not included in this value.

NOINT - Number of time intervals for which average temperatures are desired, NOINT $\leq$ 30.

NW - Number of boundaries in the shelter, NW $\leq$ 20.

P - Number of occupants.

PSAT(n) - Saturation pressure of water vapor at n °F, lb/ft^2. See Table II.

QEQUIP - Sensible heat load due to mechanical and/or electrical equipment (excluding lighting), Btu/hr.

QLITE - Sensible heat load due to lighting, Btu/hr.

ROW(k,j) - Density of material of layer k of boundary j, lb/ft^3.

R11 - Relative humidity of inlet air at beginning of occupancy.

R12 - Relative humidity of inlet air at end of each hour of occupancy.

R2 - Relative humidity in shelter at beginning of occupancy.

TA1 - Dry-bulb temperature of air exterior to shelter structure at beginning of occupancy, °F.

TA2 - Dry-bulb temperature of air exterior to shelter structure at end of each hour of occupancy, °F.

TCOIL - Effective coil temperature of air conditioning unit, °F. Suggested value is 55°F with WCOIL = 0.00921 lb water/lb dry air.

TD11 - Dry-bulb temperature of inlet air at the beginning of occupancy, °F.

TD12 - Dry-bulb temperature of inlet air at end of each hour of occupancy, °F.

TD2 - Initial shelter dry-bulb temperature, °F.

TEFF(1) - Initial shelter effective temperature, °F.

TO - Initial temperature of each boundary nodal point, °F.

TRANS(j) - Total radiation transmittance of boundary j.

TSOIL(j) - Temperature of outermost nodal point when considering a soil-backed boundary j, °F.

TWB(1) -Initial shelter wet-bulb temperature, °F.

W -Equivalent interior width of shelter, feet.

WCOIL -Humidity ratio at saturation corresponding to TCOIL, lb moisture/lb dry air. Suggested value is 0.00921 for TCOIL = 55°F.

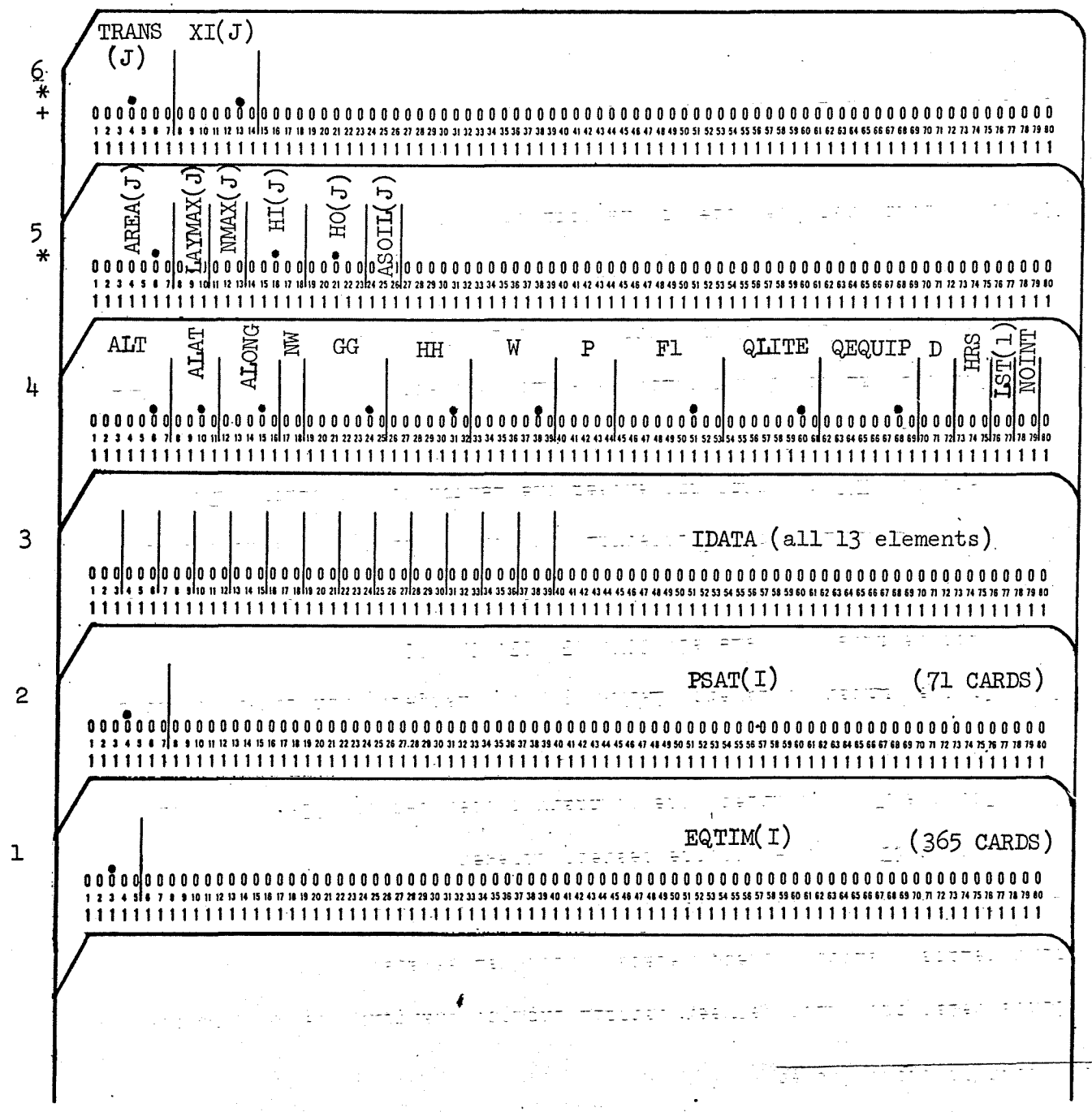
XI(j) -Inclination angle of boundary j, measured from the vertical, degrees. Values between 0° and 90° are allowed. For a vertical boundary, XI(j) = 0°.

Limitations on Input Values

Since relations exist between certain inputs, changing one necessitates adjusting related values. These related input values are:

1. If the time increment DT is varied, adjust IDATA(5), since IDATA(5) = 1 hour/DT, rounded to the nearest integer.
2. For the NW boundaries, the boundary properties of AREA(j), ASOIL(j), AZ(j), HI(j), HO(j), LAYMAX(j), NMAX(j) must correspond.
3. If the number of layers, LAYMAX(j), is changed, then layer properties must be added or deleted: CON, CP, DP, DX, ROW.
4. Equivalent dimensions GG, HH, W must correspond to the AREA(j) values.
5. The hour limits on the interval for which average temperatures are desired, INT(m), must not exceed the length of occupancy, HRS.
6. The values of $\sum_j (DP(j)/DX(j)) + 1$ must equal NMAX for each boundary.
7. Initial values of dry-bulb, wet-bulb, and effective temperature and relative humidity must correspond: TD2, TWB(1), TEFF(1), R2.
8. WCOIL must correspond to TCOIL, for the air conditioning unit.

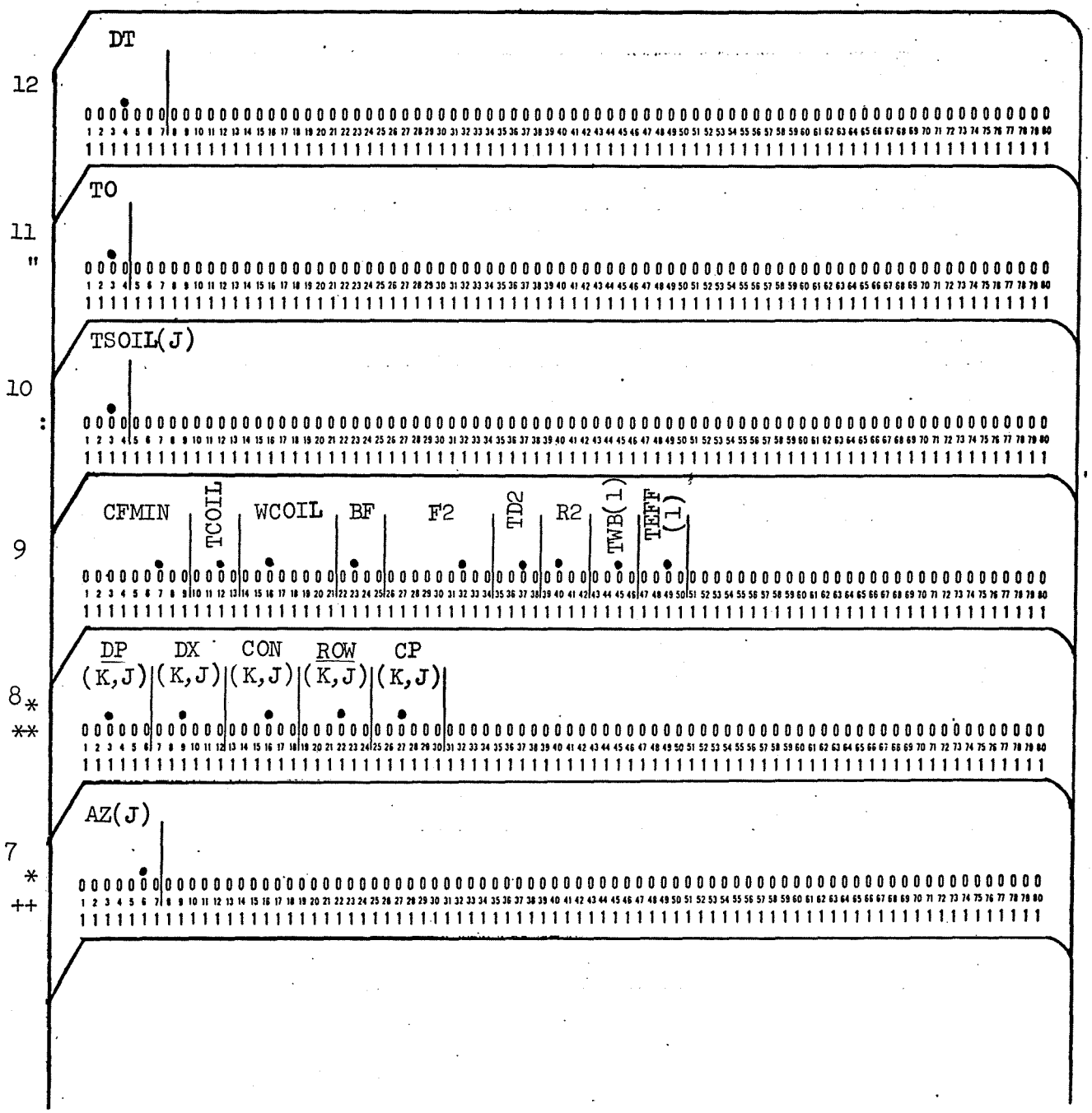
It is obvious that the size of the data deck is quite large; it is of utmost importance that the order of the data deck, as indicated in Figure 3-2, be maintained. Decimal points and field widths of the variables are also



* Note: The sequence of input cards 5-6-7-8 is repeated for each boundary in succession; i.e., for J from 1 to NW.

\+ Note: Input card 6 is included in the sequence for boundary J only if ASOIL(J) < 0.0.

Figure 3-2 Input Data Format



* See Note on preceding page.

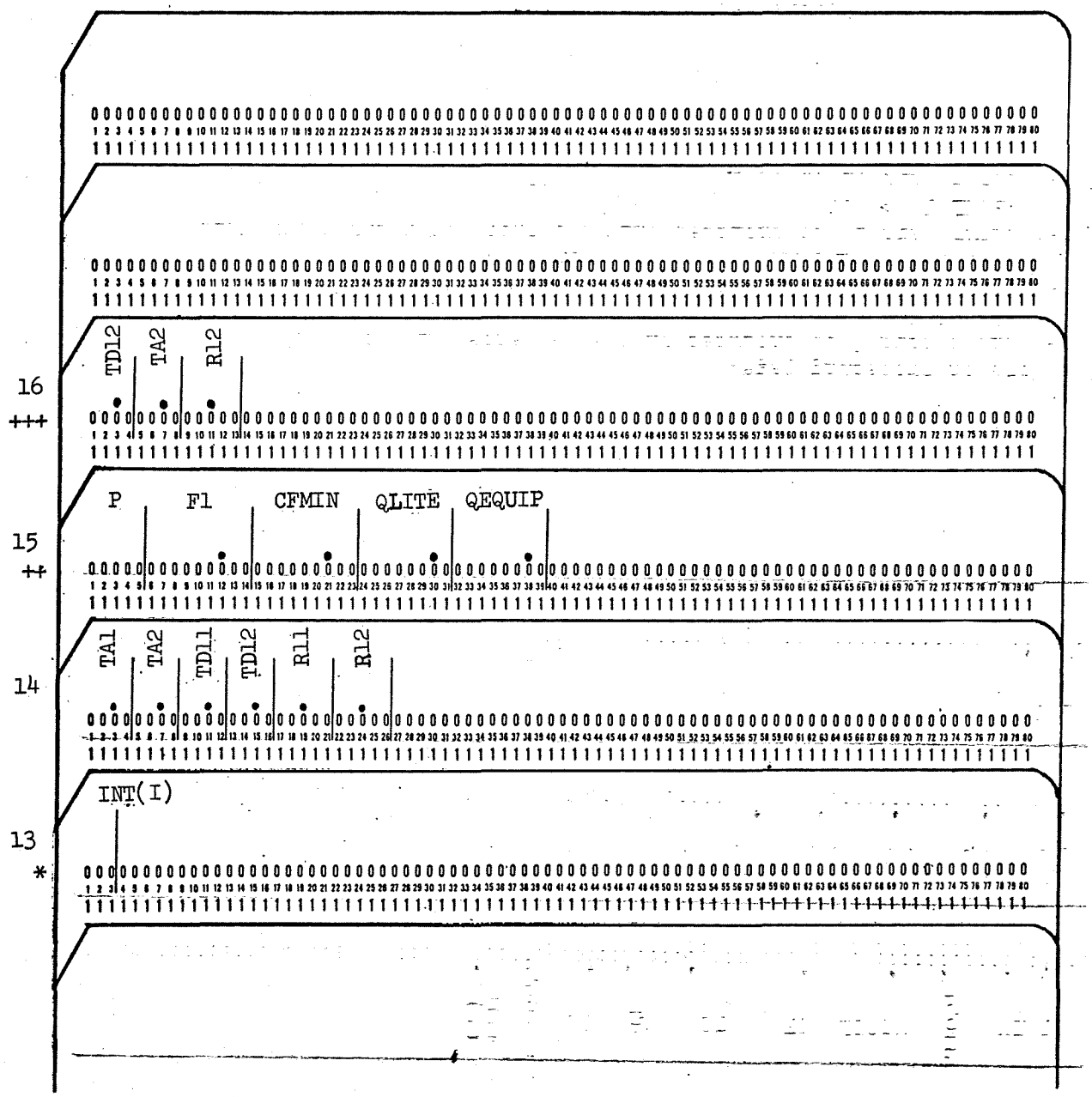
++ Note: Input card 7 is included in the sequence only if ASOIL(J) < 0.0 and XI(J) < 90.0.

** Note: Input card 8 is repeated for each layer of boundary J, i.e., for K from 1 to LAYMAX(J) for boundary J.

: Note: Input card 10 is included only for those boundaries for which ASOIL(J) > 0.0.

" Note: Input card 11 is included once if IDATA(1) = 0 . If IDATA(1) = 1 , card 11 must be repeated for each nodal point of each boundary, in succession; i.e., for K from 1 to LAYMAX(J) for each J from 1 to NW.

Figure 3-2 (Cont'd) Input Data Format



* Note: Input card 13 is included only if NOINT > 0, and is repeated for each lower and upper hour number for each interval in succession; i.e., for I from 1 to 2 * (NOINT).

++ Note: Input card 15 is included only if IDATA(12) $\leq$ 0, and is repeated for each hour of occupancy after the first; i.e., for hour numbers from 2 to HRS.

+++ Note: Input card 16 is included only if IDATA(13) $\leq$ 0, and is repeated for each hour of occupancy after the first; i.e., for hour numbers from 2 to HRS.

Figure 3-2 (Cont'd) Input Data Format

indicated in the figure. Since data may be placed only in specific fields on each data card, the easiest method of keeping the data deck ordered is to punch an appropriate identifier anywhere outside of the specified fields.

Values for the matrices EQTIM and PSAT may be found in Tables I and II. The EQTIM values are those for the year 1958, and may be considered those for any year in this century. Values of the saturation pressure as a function of dry-bulb temperature are introduced as a table with a linear interpolation scheme included in the program. These two inputs comprise the first 436 cards of a standard data deck.

If the program is used to analyze an actual shelter under actual weather conditions, hourly ambient temperature and relative humidity values are required. Soil temperatures may be considered constant over a two-week occupancy period.

Various time increments (DT) were tested by the authors to determine a compromise between accuracy of computation and length of computation. It has been found that a time increment of ten minutes (0.167 hr) produces results which are, on the average, within 0.3°F of the results calculated using 2-minute increments. The computation time is also decreased by approximately 60%, see Figure 3-3.

It should be noted that integer data values must be right-hand justified within their respective fields; if this is not the case, the machine will place zeroes in the field to the right of the right-most non-zero digit.

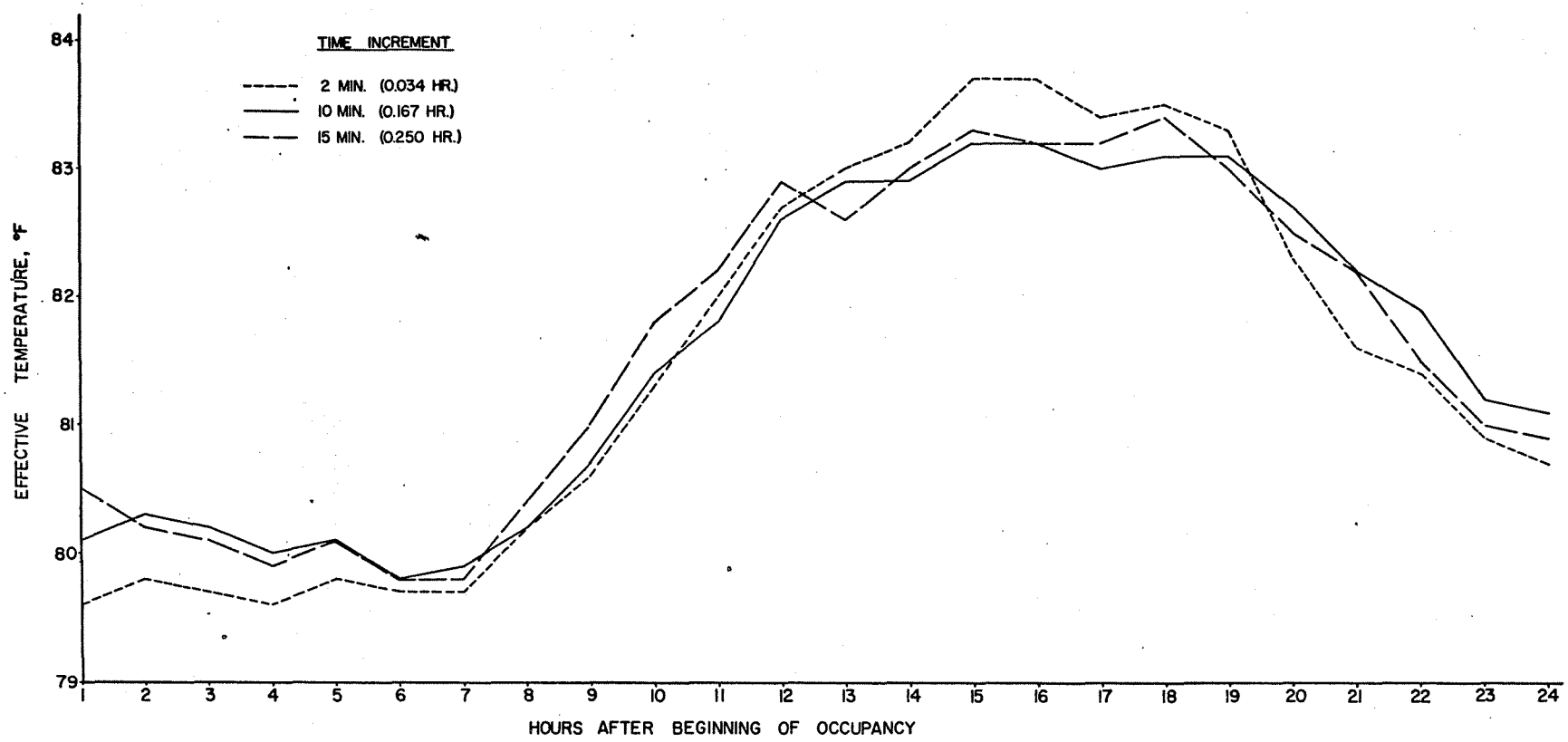


Figure 3-3 Shelter Effective Temperature Computed on Three Different Time Increments

SECTION 4

HOW TO USE SHEP

4.1 The first step in the analysis of a shelter is to describe the shelter with all of its necessary characteristics. Answer these questions on a form sheet such as that of Figure 4-1.

1. Where is the shelter located? (ALT, ALAT, ALONG).
2. What is the shelter geometry? How many separate "walls"? (NW, GG, HH, W).
3. How many occupants will be in the shelter and will this number change during the period of occupancy? (P).
4. What is the total ventilation airflow entering shelter and will it change with time? (F1).
5. What is the lighting and equipment load and is it constant? (QLITE, QEQUIP).
6. How long is the period of occupancy and when does it start (day of the year and time of day)? (D, HRS, LST(1)).
7. For each boundary, what are the values of the:
   - A. Area? (AREA).
   - B. Number of layers and number of nodal points? (LAYMAX, NMAX).
   - C. Interior and exterior film heat transfer coefficients? (HI, HO).
   - D. Control number for the wall backing? (ASOIL).
   - E. Solar radiation transmittance? (TRANS).
   - F. Inclination and azimuth angles? (XI, AZ).
8. For each layer of each boundary, what are the values of the:
   - A. Thickness? (DP).
   - B. Nodal Point Space? (DX).

1 EQTIM(1) [ ]

⋮

EQTIM(365) [ ]

2 PSAT(50) [ ]

⋮

PSAT(120) [ ]

3 IDATA(1)-(13) [ ] [ ] [ ] [ ] [ ] [ ] [ ] [ ] [ ] [ ] [ ] [ ] [ ]

4 LOCATION: ALT [ ] ft, ALAT [ ] °N, ALONG [ ] °W

GEOMETRY: NW [ ], GG [ ] ft, HH [ ] ft, W [ ] ft

OCCUPANTS: P [ ]

TOTAL VENTILATION: FI [ ] cfm

LIGHTING and EQUIPMENT: QLITE [ ] Btu/hr, QEQUIP [ ] Btu/hr

OCCUPANCY PERIOD: D [ ], HRS [ ] hours, LST(I) [ ], NOINT [ ] intervals

Figure 4-1 Form Sheet for Organizing Input Data

5-6-7 For each boundary:

Boundary No.	AREA	LAYMAX	NMAX	HI	HO	ASOIL	TRANS	XI	AZ
1									
2									
3									
4									
5									
6									
7									
8									
9									
10									
11									
12									
13									
14									
15									
16									
17									
18									
19									
20									

Figure 4-1 (Cont'd) Form Sheet for Organizing Input Data

8 For each layer of each boundary: DP(ft), DX(ft), CON(Btu/hr-ft-°F), ROW(lb/ft^3), CP(Btu/lb-°F)

	layer	boundary 1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
DP	1																				
	2																				
	3																				
	4																				
	5																				
DX	1																				
	2																				
	3																				
	4																				
	5																				
CON	1																				
	2																				
	3																				
	4																				
	5																				
ROW	1																				
	2																				
	3																				
	4																				
	5																				
CP	1																				
	2																				
	3																				
	4																				
	5																				

Figure 4-1 (Cont'd) Form Sheet for Organizing Input Data

9 AIR CONDITIONING: CFMIN [ ] cfm, TCOIL [ ] °F, WCOIL [ ] lb moisture/lb dry air, BF [ ], F2 [ ] cfm

INITIAL CONDITIONS: TD2 [ ] °F, R2 [ ], TWB(I) [ ] °F, TEFF(I) [ ] °F

10 SOIL TEMPERATURES:

Boundary No.	Temperature

11 INITIAL NODAL-POINT TEMPERATURES: TO [ ] °F or Individual Values

Boundary No. \ Nodal-Point	1	2	3	4	... 40
1					
2					
⋮ 20					

12 TIME INCREMENT: DT [ ] hr

13 INTERVAL LIMITS: [ ] TO [ ]

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Figure 4-1 (Cont'd) Form Sheet for Organizing Input Data

14 INITIAL INLET CONDITION: TAI [ ] °F, TA2 [ ] °F, TDII [ ] °F, TDI2 [ ] °F, RII [ ] RI2 [ ]

15-16 For each hour of occupancy:-

Hour No.	TA2	TDI2	RI2	P	FI	CFMIN	QLITE	QEQUIP

Figure 4-1 (Cont'd) Form Sheet for Organizing Input Data

C. Thermal Conductivity? (CON).

D. Density? (ROW).

E. Specific Heat? (CP).

9. If air conditioning is involved, what air flow is going through the cooler (CFMIN); what is the effective surface coil temperature (TCOIL) and the humidity ratio corresponding to this dewpoint temperature (WCOIL); what is the bypass factor (BF)? What is the amount of outside air entering the system (F2)?

10. What are the initial conditions inside the shelter? (TD2, R2, TWB(1), TEFF(1). What are the initial wall temperatures? (TO).

11. What are the soil temperatures around the shelter? (TSOIL).

12. For computational purposes:

    A. How many intervals are there for which average temperatures are required, and what are their hour limits? (NOINT, INT).

    B. What time increment should shelter temperatures be calculated on? (DT).

13. What are the hourly values of inlet temperature and relative humidity during occupancy? (TA2, TD12, R2). What are the values of occupancy variables (P, F1, CFMIN, QLITE, QEQUIP)?

4.2 After the data is determined, options in the program must be decided upon. Will the analysis include:

1. Initially isothermal boundaries? (IDATA(1)).

2. Adiabatic or non-adiabatic boundaries? (IDATA(6)).

3. Air conditioning? (IDATA(7)).

4. Printout of the table of hourly values? (DATA(11)).

5. Constant or time-varying occupancy variables? (IDATA(12)).

6. Constant or time-varying inlet conditions? (IDATA(13)).

4.3 Once the data has been determined and the options have been chosen, initial conditions in the shelter system must be set. Four quantities must be given to specify the shelter atmosphere: dry-bulb, wet-bulb and effective temperatures, and the relative humidity. It is mandatory that these values correspond to each other.

Initial wall temperatures should approximate the initial shelter dry-bulb temperature within a few degrees. While stability of solution is not a problem in the code, initial conditions should be fairly accurate so that the number of calculations required to eliminate the errors introduced by the incorrect estimate of the shelter and boundary temperatures is minimized.

4.4 After all values necessary for an analysis have been determined, the code user is ready to create the data deck. The format of each data card and the order of the cards is indicated in Figure 3-2. Of course, the order of the deck is of major importance and an identification on each data card will help keep it in its correct position.

4.5 The SHEP code is written in FORTRAN IV specifically for the CDC 3600 computer system and, therefore, utilizes certain library functions. These include:

Form	Definition
ABSF(X)	Absolute value of X
ATAN(X)	Arctangent X radians
COS(X)	Cosine X radians
EXP(X), EXPF(X)	e to the Xth power
SIN(X)	Sine X radians
SQRT(X)	Square root of X
TANF(X)	Tangent X radians

If the code is re-written for another computer system, these library functions, or their equivalents, must be supplied.

4.6 If the values of certain input data and certain computed variables exceed specified ranges, error messages will appear in the output as per Table III, p. 2-16.

The SHEP code requires two memory banks ($65\frac{k}{}$ locations) for the code and the accompanying matrices; in fact, the AINV matrix, which contains the inverted matrices of the temperature coefficients in the boundary heat-transfer equations, fills one bank (76,400 out of 77,777 (octal) words). Thus, a BANK statement is another requirement. There are only two computer systems other than the 3600 that have this amount of storage known to the authors at the time of this writing; they are the CDC 6600 and the UNIVAC 1108. Although several smaller computers can be adapted and enlarged, this requires special facilities. Therefore, in terms of storage requirements, the SHEP code can be run on any of these three computing systems.

SECTION 5

INTERPRETATION OF OUTPUT

The output of the SHEP program is a tabulation of the instantaneous values of the thermal loads affecting the shelter and the shelter psychrometric condition for the last increment of each hour of occupancy, see Figure 5-1. It must be remembered that these values are instantaneous and, while they reflect trends in the shelter system, interpolation between hourly values may be invalid. Also, hourly thermal loads determine the resultant shelter temperature, not vice versa. The 3600 computer system printer includes a procedure for rounding output to the format specified. Thus, the thermal loads are rounded in value to the nearest integer.

The air conditioning, boundary and condensation heat loads, when positive, represent energy lost from the shelter system; all other positive loads are energy additions. In the SHEP code, the assumptions associated with the calculations of the air conditioning, moisture condensation, and transmitted solar radiation loads generally lead to conservative estimates of these loads.

Maximum and minimum shelter temperatures and the hours of their occurrence are indicated. Average temperatures are computed for the entire occupancy period, for each full day of occupancy, and for specific intervals determined by the code user.

NOMINAL OCCUPANT ACTIVITY LEVEL 400 BTU/HR -OCCUPANT

VALUES ARE FOR LAST TIME INCREMENT OF EACH HOUR

LOADS (BTU/HR)

TIME HR	VENT RATE CFM/ OCC	DRT DEG F	WBT DEG F	ET DEG F	AIRCOND	BOUNDARY	CONDEN.	TRANS. SOLAR	METABOLIC SENSIBLE	METABOLIC LATENT	LIGHTING	EQUIPMENT
1	15.0	71.6	70.4	71.1	240042	-8124	0	0	281517	126522	6250	5000
2	15.0	72.1	70.4	71.4	243828	-35143	0	0	288206	120585	6250	5000
3	15.0	71.4	70.4	71.0	211179	-7494	0	0	281360	126678	6250	5000
4	15.0	72.1	70.5	71.4	234859	-44255	0	0	290442	118649	6250	5000
5	15.0	71.3	70.1	70.8	208811	-4419	0	0	280593	127302	6250	5000
6	15.0	72.4	70.5	71.6	214527	-47117	0	0	291142	118093	6250	5000
7	15.0	71.1	70.1	70.7	201581	3941	0	0	278501	129103	6250	5000
8	15.0	71.8	70.4	71.2	249394	-18241	0	0	284033	123348	6250	5000
9	15.0	72.3	70.5	71.5	268959	-22288	0	0	285035	123418	6250	5000
10	15.0	72.4	70.6	71.6	283330	5697	0	0	278060	129512	6250	5000
11	15.0	72.6	71.7	72.2	293154	22867	0	0	273733	132668	6250	5000
12	15.0	73.5	72.4	73.0	321451	34356	0	0	270817	135046	6250	5000
13	15.0	74.0	72.4	73.3	303665	35375	-3934	0	270558	135308	6250	5000
14	15.0	74.0	72.0	73.1	322330	52929	-11092	0	266069	139486	6250	5000
15	15.0	74.7	72.4	73.6	334872	56870	0	0	265056	140358	6250	5000
16	15.0	74.7	72.4	73.6	310299	83201	4888	0	258239	146342	6250	5000
17	15.0	74.5	72.1	73.5	327599	59815	0	0	264298	140971	6250	5000
18	15.0	74.3	72.3	73.4	329595	73790	0	0	260685	144169	6250	5000
19	15.0	74.4	72.3	73.5	329482	48923	0	0	267097	138600	6250	5000
20	15.0	73.1	72.2	72.7	302115	36330	17841	0	270315	135463	6250	5000
21	15.0	72.7	71.9	72.3	286673	9840	-6458	0	277020	129618	6250	5000
22	15.0	72.8	72.0	72.4	259851	10388	0	0	276882	129757	6250	5000
23	15.0	72.3	71.4	71.9	252150	-11170	0	0	282276	125301	6250	5000
24	15.0	71.9	71.2	71.6	247122	-6569	0	0	281129	126301	6250	5000

MAX. DRY-BULB TEMP. DURING OCCUPANCY 74.7 AT 15 HOURS AFTER BEGINNING OF OCCUPANCY

MIN. DRY-BULB TEMP. DURING OCCUPANCY 71.1 AT 7 HOURS AFTER BEGINNING OF OCCUPANCY

MAX. WET-BULB TEMP. DURING OCCUPANCY 72.4 AT 16 HOURS AFTER BEGINNING OF OCCUPANCY

MIN. WET-BULB TEMP. DURING OCCUPANCY 70.1 AT 5 HOURS AFTER BEGINNING OF OCCUPANCY

MAX EFFECTIVE TEMP. DURING OCCUPANCY 73.6 AT 16 HOURS AFTER BEGINNING OF OCCUPANCY

MIN EFFECTIVE TEMP. DURING OCCUPANCY 70.7 AT 7 HOURS AFTER BEGINNING OF OCCUPANCY

TIME-AVERAGE TEMPERATURE VALUES

		DBT	WBT	ET
FOR ENTIRE DURATION OF OCCUPANCY		72.8	71.4	72.2
FOR EACH DAY OF OCCUPANCY				
	DAY 1	72.8	71.4	72.2
FOR SPECIFIC INTERVALS	HRS			
	3- 6	71.8	70.4	71.2
	9- 15	73.3	71.7	72.6
	15- 24	73.5	72.0	72.9
	12- 18	74.2	72.3	73.3

Figure 5-1 Typical Output of SHEP Code

SECTION 6

SAMPLE PROBLEM

To illustrate the use of the SHEP code, a shelter defined by the values listed in Table IV is considered. A sketch of the sample shelter is shown in Figure 601; the rectangular shelter area is in the basement of a multi-story building. It is defined by eight opaque boundaries, four of which are multi-layered; three are soil-backed, two boundaries are exposed to ambient air, and the remaining three are exposed to interior spaces. See Figures 2-1 and 2-2. Occupancy is limited to 1000 persons for 24 hours at a constant ventilation rate of 15 cfm/occupant. The air conditioning system is assumed to be operating during occupancy with a constant airflow rate of 8 cfm-occupant and the shelter lighting and equipment add a constant thermal load of 11,250 Btu/hr. The weather affecting the shelter is that which occurred at Montgomery, Alabama during 1 August, 1963.

The output of this shelter analysis is shown in Figure 501. It can be seen that the shelter temperatures vary in a diurnal cycle, as would be expected; they are lowest in the early norming and are highest in the late afternoon. Air conditioning also can be seen to vary directly with the shelter temperature. In the cooler hours of the day, i.e., from 10 PM to 9 AM, the shelter boundaries are warmer than the shelter atmosphere, and energy is transferred from the boundaries to the shelter air, as is indicated by the negative signs on the boundary heat losses for these hours. During the other hours of the day, the shelter is warmer than the boundaries and energy leaves the shelter.

If the value of condensation heat loss is negative, this corresponds to evaporation of the condensate on the walls, and an addition of energy to

TABLE IV

SAMPLE INPUT DATA

1 EQTIM(1) [. . .]

⋮

EQTIM(365) [. . .]

2 PSAT(50) [. . .]

⋮

PSAT(120) [. . .]

3 IDATA(1)-(13) [1] [0] [4] [1] [6] [1] [1] [0] [0] [0] [1] [1] [0]

4 LOCATION: ALT [2 1 0 . 0] ft, ALAT [8 6 . 4] °N, ALONG [3 2 . 3] °W

GEOMETRY: NW [8], GG [7 5 . 0] ft, HH [1 0 . 0] ft, W [1 3 4 . 0] ft

OCCUPANTS: P [1 0 0 0]

TOTAL VENTILATION: FI [1 5 0 0 0 . 0 0] cfm

LIGHTING and EQUIPMENT: QLITE [6 2 5 0 . 0] Btu/hr, QEQUIP [5 0 0 0 . 0] Btu/hr

OCCUPANCY PERIOD: D [2 1 3], HRS [2 4] hours, LST(1) [0], NOINT [4] intervals

TABLE IV (Cont'd)

SAMPLE INPUT DATA

5-6-7 For each boundary

Boundary No.	AREA	LAYMAX	NMAX	HI	HO	ASOIL	TRANS	XI	AZ
1	3,7,5,.0	2	2,0	1.4,6	0.	1			
2	6,7,0,.0	2	2,0	1.4,6	0.	1			
3	3,7,5,.0	2	1,0	1.4,6	0.1,7	-1	0.0,0,0	0.0	1,8,0,.0
4	6,7,0,.0	2	1,0	1.4,6	0.1,7	-1	0.0,0,0	0.0	2,7,0,.0
5	1,0,0,5,0,.0	2	1,9	1.0,8	0.	1			
6	1,3,4,0,.0	1	5	1.4,6	1.4,6	0			
7	7,5,0,.0	1	5	1.4,6	1.4,6	0			
8	1,0,0,5,0,.0	1	2,1	1.6,3	1.0,8	0			
9									
10									
11									
12									
13									
14									
15									
16									
17									
18									
19									
20									

TABLE IV (Cont'd)

SAMPLE INPUT DATA

8 For each layer of each boundary: DP(ft), DX(ft), CON(Btu/hr-ft-°F), ROW(lb/ft^3), CP(Btu/lb-°F)

	layer	boundary 1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
DP	1	0.6,6,7	0.6,6,7	0.3,3,4	0.3,3,4	0.6,6,7	0.3,3,4	0.3,3,4	0.5,0,0												
	2	1,0.0,0,0	1,0.0,0,0	0.3,3,4	0.3,3,4	1,0.0,0,0															
	3																				
	4																				
	5																				
DX	1	0.0,8,3	0.0,8,3	0.0,8,3	0.0,8,3	0.0,8,3	0.0,8,3	0.0,8,3	0.0,2,5												
	2	1.0,0,0	1.0,0,0	0.0,8,3	0.0,8,3	1.0,0,0															
	3																				
	4																				
	5																				
CON	1	0.4,7	0.4,7	0.2,8	0.2,8	0.4,7	0.6,0	0.6,0	0.6,1												
	2	0.3,0	0.3,0	0.4,7	0.4,7	0.3,0															
	3																				
	4																				
	5																				
ROW	1	1,4,4.0,0	1,4,4.0,0	1,2,0.0,0	1,2,0.0,0	1,4,4.0,0	1,1,0.0,0	1,1,0.0,0	1,1,9.0,0												
	2	1,2,8.0,0	1,2,8.0,0	1,4,4.0,0	1,4,4.0,0	1,2,8.0,0															
	3																				
	4																				
	5																				
CP	1	0.2,1,0	0.2,1,0	0.2,0,0	0.2,0,0	0.2,1,0	0.2,0,0	0.2,0,0	0.2,1,0												
	2	0.4,4,0	0.4,4,0	0.2,1,0	0.2,1,0	0.4,4,0															
	3																				
	4																				
	5																				

TABLE IV (Cont'd)

SAMPLE INPUT DATA

9 AIR CONDITIONING: CFMIN [,8,0,0,0.,0,0] cfm, TCOIL [5,5.,0] °F, WCOIL [,0.,0,0,9,2,1] lb moisture/lb dry air, BF [,0.,1,5], F2 [,3,0,0,0.,0,0] cfm

INITIAL CONDITIONS: TD2 [8,1.,0] °F, R2 [,0.,7,8], TWB(I) [7,5.,5] °F, TEFF(I) [7,8.,0] °F

10 SOIL TEMPERATURES:

Boundary No.	Temperature [,.,]
1	75.0
2	75.0
5	75.0
⋮	

11 INITIAL NODAL-POINT TEMPERATURES: TO [8,1.,0] °F or Individual Values

12 TIME INCREMENT: DT [,0.,1,6,7] hr

13 INTERVAL LIMITS:

[,3]	TO	[,6]
9		15
15		24
12		18

Boundary No. \ Nodal-Point	1	2	3	4	. . 40
1					
2					
⋮ 20					

TABLE IV (Cont'd)

SAMPLE INPUT DATA

14 INITIAL INLET CONDITION: TA1 [75.0] °F, TA2 [75.0] °F, TDI1 [75.0] °F, TDI2 [75.0] °F, RI1 [.09.0] RI2 [.09.0]

15-16 For each hour of occupancy:

Hour No.	TA2	TDI2	RI2	P	FI	CFMIN	QLITE	QEQUIP

Boundary No.	Location
1	South Wall (lower half)
2	West Wall (lower half)
3	South Wall (upper half)
4	West Wall (upper half)
5	Floor
6	East Wall
7	North Wall
8	Ceiling

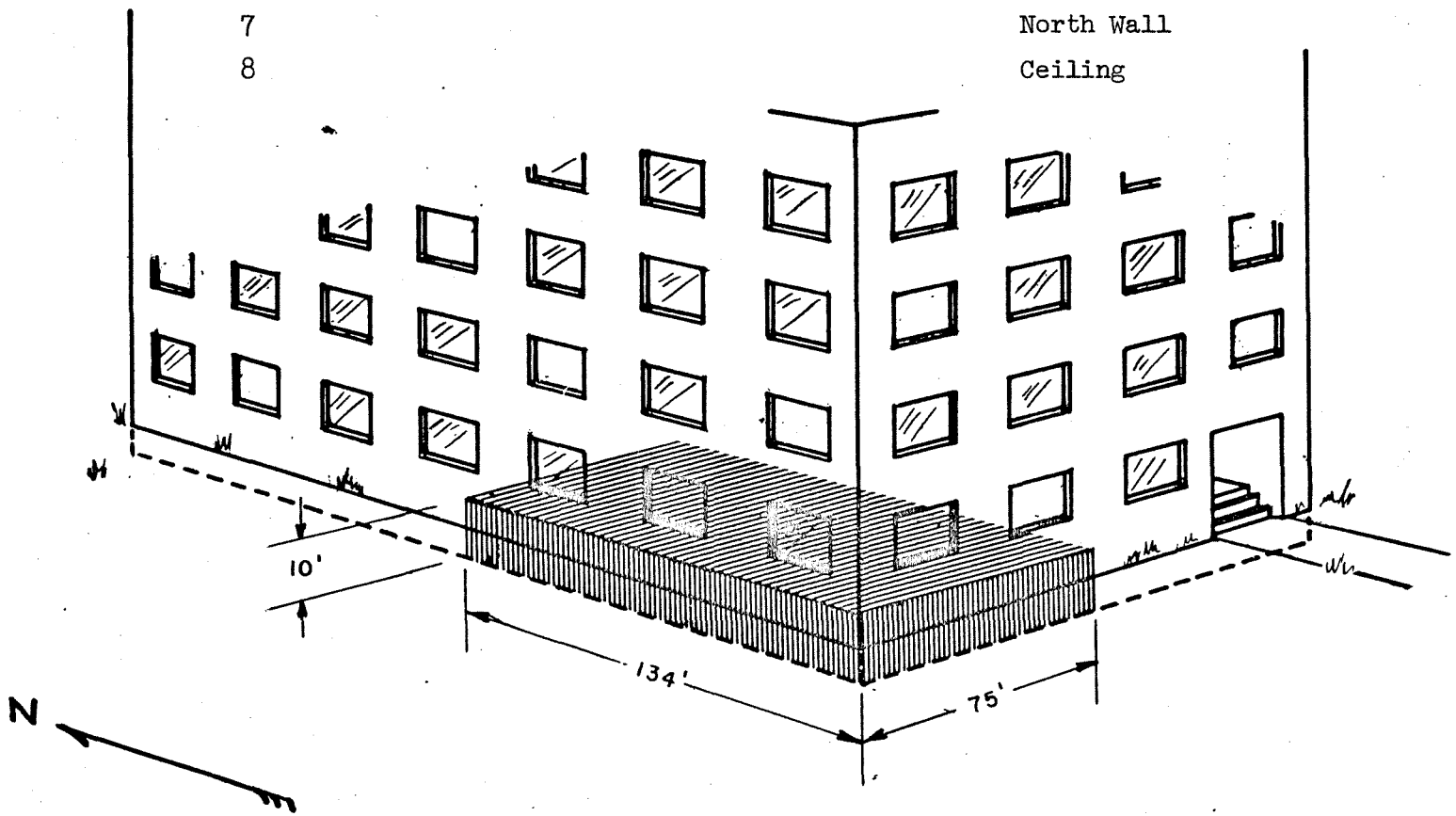

Figure 6-1 Sketch of Shelter Area Used in Sample Problem

the shelter temperature. Positive value of the condensation heat load indicates moisture is condensing on the shelter boundaries and energy is being removed from the shelter air. There is a check in the code to prevent the amount of re-evaporated moisture from exceeding the amount previously condensed.

Metabolic loads are predicted, using the relations developed by Houghten[5], based on both the shelter dry-bulb and effective temperatures. Since these vary by only a few degrees during occupancy, the total metabolic load for each hour is approximately constant.

SECTION 7

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APPENDICES

APPENDIX A

DETERMINATION OF SHELTER ENVIRONMENT

The study of the interrelationships among ventilation rate, thermal load, and boundary losses in the shelter is based on the assumption that the shelter atmosphere may be represented by one psychrometric condition. A shelter model that will take into account the thermal effects of solar radiation, air-conditioning, moisture condensation and re-evaporation, and boundary losses is developed according to the following assumptions:

1) the air within the shelter is completely and instantaneously mixed;
2) the film heat transfer coefficients are constant for any one boundary surface;
3) the radiative energy transfer within the shelter can be neglected;
4) the condition of the air exhausted from the shelter is the condition of the shelter atmosphere;
5) the thermal and physical properties of the structural materials and of air are not temperature-dependent;
6) the incident solar radiation is absorbed on the outer surface of the boundaries and appears as conducted energy or is transmitted into the shelter and is considered an instantaneous load with the lighting and equipment loads; and
7) the thermal loads and the psychrometric states of the inlet and exhaust air are constant over short time intervals.

The shelter model is therefore a volume enclosed by boundaries into which sensible and latent heat loads and ventilating air are introduced and from which air is exhausted and energy is lost, see Figure A-1. The governing equations of the enclosed volume are derived from the conservation of mass and the conservation of energy.

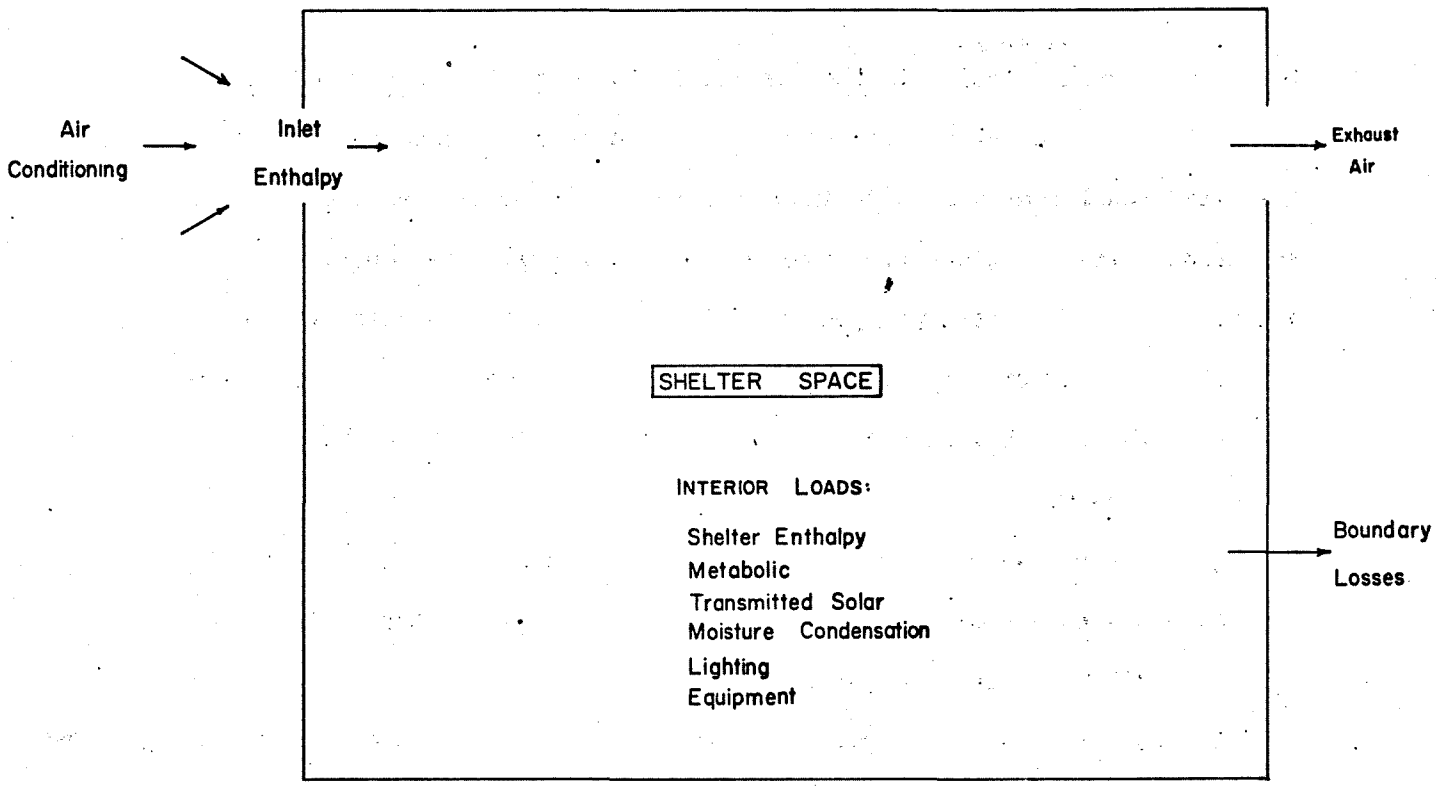


Figure A-1 Shelter Energy Transfer

$$\frac{\partial}{\partial t}(H) + \frac{\partial}{\partial t}(H_S) + \frac{\partial}{\partial t}(Q_M + Q_L + Q_E) - \frac{\partial}{\partial t}(Q_W + Q_{AC}) = 0 \qquad (1)$$

where H = enthalpy of the exchanged air, Btu

H_S = enthalpy of the shelter, Btu

Q_M = metabolic energy of occupants, Btu

Q_L = energy due to shelter lighting, Btu

Q_E = energy due to other shelter equipment, Btu

Q_W = energy conducted through shelter boundaries, Btu

Q_{AC} = energy removed from shelter system by air conditioner, Btu

Integrating equation (1) over the time increment δt yields

$$(H_1 - H_2) + (H_{S,1} - H_{S,2}) + Q_M + Q_L + Q_E - Q_W - Q_{AC} = C \qquad (2)$$

where the subscripts 1 and 2 refer to the beginning and the end of the time increment, respectively. Although this analysis is time-varying in the sense that results using successive time increments represent changing conditions, by assumption (7), the thermal load values and the psychrometric states of the inlet and exhaust air in this equation are all considered constant during the time increment. Therefore, there is no heat-storage term during the time increment and C = 0.

Conservation of mass may be applied to both the dry air and the water vapor in the shelter system. When it is applied to the vapor:

$$\frac{\partial}{\partial t}(M_V) + \frac{\partial}{\partial t}(M_{V,S}) + \frac{\partial}{\partial t}(M_{V,M}) - \frac{\partial}{\partial t}(M_{V,COND}) = 0 \qquad (3)$$

where M_V = mass of water vapor in the exchanged air, lb.

$M_{V,M}$ = mass of water vapor introduced by the shelter occupants, lb.

$M_{V,S}$ = mass of water vapor in the shelter air, lb.

$M_{V,COND}$ = mass of water vapor removed by condensation, lb.

Integration yields

$$(M_{V,1} - M_{V,2}) + (M_{V,S,1} - M_{V,S,2}) + M_{V,M} - M_{V,COND} = 0 \qquad (4)$$

The energy balance for dry air in the system is given by

$$\frac{\partial}{\partial t}(M_a) + \frac{\partial}{\partial t}(M_{a,s}) = 0 \tag{5}$$

where M_a = mass of dry air in the exchanged air, lb.

$M_{a,s}$ = mass of dry air in the shelter air, lb.

or $$(M_{a,1} - M_{a,2}) + (M_{a,s,1} - M_{a,s,2}) = 0 \tag{6}$$

Let $$\delta Q = H_1 + H_{S1} + Q_M + Q_L + Q_E - Q_W - Q_{AC} \tag{7}$$

$$M_{V,O} = M_{V,1} + M_{V,S,1} + M_{V,M} - M_{V,COND} \tag{8}$$

$$M_{a,o} = M_{a,1} + M_{a,s,1} \tag{9}$$

then $$\delta Q = H_2 + H_{S,2} \tag{10}$$

$$M_{V,O} = M_{V,2} + M_{V,S,2} \tag{11}$$

$$M_{a,o} = M_{a,2} + M_{a,s,2} \tag{12}$$

Now $$H_{S,2} = M_{a,S,2}\, h_{a,s,2} + M_{V,S,2} h_{V,S,2} \tag{13}$$

and $$H_2 = M_{a,2}\, h_{a,2} + M_{V,2}\, h_{v,2} \tag{14}$$

where the lower case h's refer to specific enthalpies (Btu/lb).

Since the ventilating air leaves at the shelter condition,

$$h_{a,2} = h_{a,S,2} \tag{15}$$

and

$$h_{V,2} = h_{V,S,2} \tag{16}$$

Substituting this value for the incremental energy δQ:

$$\delta Q = M_{a,O}\, h_{a,S,2} + M_{V,O}\, h_{V,S,2} \tag{17}$$

Now specific enthalpies of dry air and water vapor may be given as functions of dry-bulb temperature:

$$\left.\begin{aligned} h_a &= 0.24\ T_{db} \qquad (18) \\ \text{and} \quad & \\ h_v &= 1061.0 + 0.444\ (T_{db}) \qquad (19) \end{aligned}\right\} \text{for } 32.2°F \leq T_{db} \leq 150°F$$

Combining equations (17) through (19) and solving for the dry-bulb temperature leads to

$$T_{db} = \frac{\delta Q - 1061\ M_{V,0}}{0.444\ M_{V,0} + 0.24\ M_{a,o}} \qquad (20)$$

This represents the shelter dry-bulb temperature at the end of the time increment $\delta\tau$.

Expressions for $M_{a,o}$ and $M_{V,0}$ can be found, since

$$M_{a,2} = 60\ \dot{F}_2 \rho_{a,2}\ \delta\tau \qquad (21)$$

$$M_{V,2} = 60\ \dot{F}_2 \rho_{v,2}\ \delta\tau \qquad (22)$$

$$M_{a,s,2} = V \rho_{a,s,2} \qquad (23)$$

and $$M_{V,S,2} = V \rho_{v,S,2} \qquad (24)$$

where V = shelter volume, ft^3

$\rho_{a,2}$ = density of dry air leaving shelter, lb/ft^3

$\rho_{v,2}$ = density of water vapor leaving shelter, lb/ft^3

$\rho_{a,s,2}$ = density of dry air in shelter, lb/ft^3.

$\rho_{v,s,2}$ = density of water vapor in shelter, lb/ft^3

and $\dot{F}_2$ = mass flow rate of exhaust air, lb/hr.

We have assumed that

$$\rho_{a,2} = \rho_{a,s,2} \tag{25}$$

and

$$\rho_{v,2} = \rho_{v,s,2} \tag{26}$$

Therefore, we obtain the expression:

$$M_{V,o} = \rho_{v,2} (60 \dot{F}_2 \delta \tau + V) \tag{27}$$

and

$$M_{a,o} = \rho_{a,2} (60 \dot{F}_2 \delta \tau + V) \tag{28}$$

Now, when these equations are solved for the ventilation rate $\dot{F}_2$,

$$\dot{F}_2 = \frac{M_{a,o} - \rho_{a,2} V}{60 \delta \tau \rho_{a,2}} = \frac{M_{V,o} - \rho_{V,2} V}{60 \delta \tau \rho_{v,2}} \tag{29}$$

It is assumed that the densities of dry air and of water vapor may be determined from the perfect-gas law: Therefore,

$$\rho_v = \frac{P_v}{R_v (T_{db} + 459.69)} \tag{30}$$

and

$$\rho_a = \frac{P_b - P_v}{R_a (T_{db} + 459.69)} \tag{31}$$

where P_b = barometric pressure, lb/ft^2

P_v = partial pressure of water vapor, lb/ft^2

R_v = gas constant for water vapor, ft-lb/lb mole - °R

and R_a = gas constant for dry-air, ft-lb/lb mole - °R

with

$$P_b = (9.8 \times 10^{-7}) A^2 - 0.0759 A + 2116.2 \tag{32}$$

where A = altitude, ft.

Now, the partial pressure of water vapor is expressible as

$$P_v = r P_S \tag{33}$$

where r = relative humidity in the shelter

and P_S = saturation pressure of water vapor, lb/ft^2

Saturation pressure varies with dry-bulb temperature according to

$$P_S = 5.132 \exp(0.0329\ T_{db}) \tag{34}$$

Using the values

$$R_a = 53.35 \text{ ft-lb/lb mole - °R}$$

$$\text{and } R_v = 85.71 \text{ ft-lb/lb mole - °R}$$

leads to

$$P_v = r\,(5.132 \exp(0.0329\ T_{db})) \tag{35}$$

$$\rho_v = \frac{r}{(T_{db} + 459.69)}\ (0.05987 \exp(0.0329\ T_{db}) \tag{36}$$

$$\text{and } \rho_a = \frac{1}{T_{db} + 459.69}\ [1.84 \times 10^{-8} A^2 - 0.00142A$$

$$+ 35.68 - r(0.0962 \exp(0.0329\ T_{db})\ ] \tag{37}$$

Since $$\frac{M_{a,o}}{\rho_{a,2}} = \frac{M_{v,o}}{\rho_{v,2}} \tag{37}$$

from equations (27) and (28), we can evaluate the last three equations to obtain

$$P_v = \frac{P_b}{1 + 0.6224\ (\frac{M_{a,o}}{M_{v,o}})} \tag{39}$$

Relative humidity, as given by equation (33), becomes

$$r = \frac{P_b}{(5.132\ e^{(0.0329\ T_{db})})\ (1 + 0.6224\ (M_{a,o}/M_{v,o})} \tag{40}$$

To summarize, the two equations necessary to compute the shelter condition are (20) and (40). The quantities in these equations may be computed as outlined above. Although the dry-bulb temperature and relative humidity uniquely determine the condition of the shelter air,

it is desired to express this condition in terms of dry-bulb temperature and wet-bulb temperature.

The wet-bulb temperature can be determined using the Carrier equation:

$$P_V = P_S' - \left(\frac{(P_b - P_s')(T_{db} - T_{wb})}{2800.0 - 1.3\ T_{wb}}\right) \tag{41}$$

where P_S' = saturation pressure at wet-bulb temperature, lb/ft^2

T_{wb} = wet-bulb temperature, °F

P_S' may be evaluated from equation (34) as

$$P_S' = 5.132 \exp(0.0329\ T_{wb}) \tag{42}$$

P_V is obtained from equation (39). Equation (41) is then a transcendental equation in T_{wb} and may be solved by an iteration procedure. After both the dry-bulb and wet-bulb temperatures are known, the effective temperature may then be calculated from

$$ET = \frac{107.5\ T_{db} - 45.2\ T_{wb}}{62.3 + T_{db} - T_{wb}} \quad \text{for} \begin{cases} 45°F \le T_{db} \le 110°F \\ 30°F \le T_{wb} \le 100°F \end{cases} \tag{43}$$

APPENDIX B

DETERMINATION OF SOLAR RADIATION INTENSITY

B-1 Determination of the Sun's Altitude and Azimuth Angles

Consider an earth-centered right-handed rectilinear coordinate system with the Y-axis directed toward the sun and with the X-Y plane that of the equator, see Figure B-1. The unit normal vectors $\vec{i}$, $\vec{j}$, and $\vec{k}$ are parallel to the X, Y and Z axes, respectively. The rays of the sun are parallel to the unit vector $\vec{s}$. The unit vector $\vec{n}$ at a point on the surface of the earth P is normal to the position vector of P and oriented toward the north pole. The position vector is parallel to the unit vector $\vec{r}$. The point P is located on the surface of the earth by the hour angle, θ, and the latitude angle, ϕ.

Now $$\vec{r} = \cos\Phi \sin\theta\, \vec{i} - \cos\Phi \cos\theta\, \vec{j} + \sin\Phi\, \vec{k} \qquad (1)$$

$$\vec{s} = \cos\eta\, \vec{j} + \sin\eta\, \vec{k} \qquad (2)$$

where: η = declination angle of the sun

The sun's zenith angle, ψ, is given by

$$\psi = \arccos(\vec{r} \cdot \vec{s})$$

$$= \arccos(\sin\Phi \sin\eta - \cos\Phi \cos\theta \cos\eta) \qquad (3)$$

The sun's altitude angle, β, is

$$\beta = \frac{\pi}{2} - \psi \qquad (4)$$

Thus

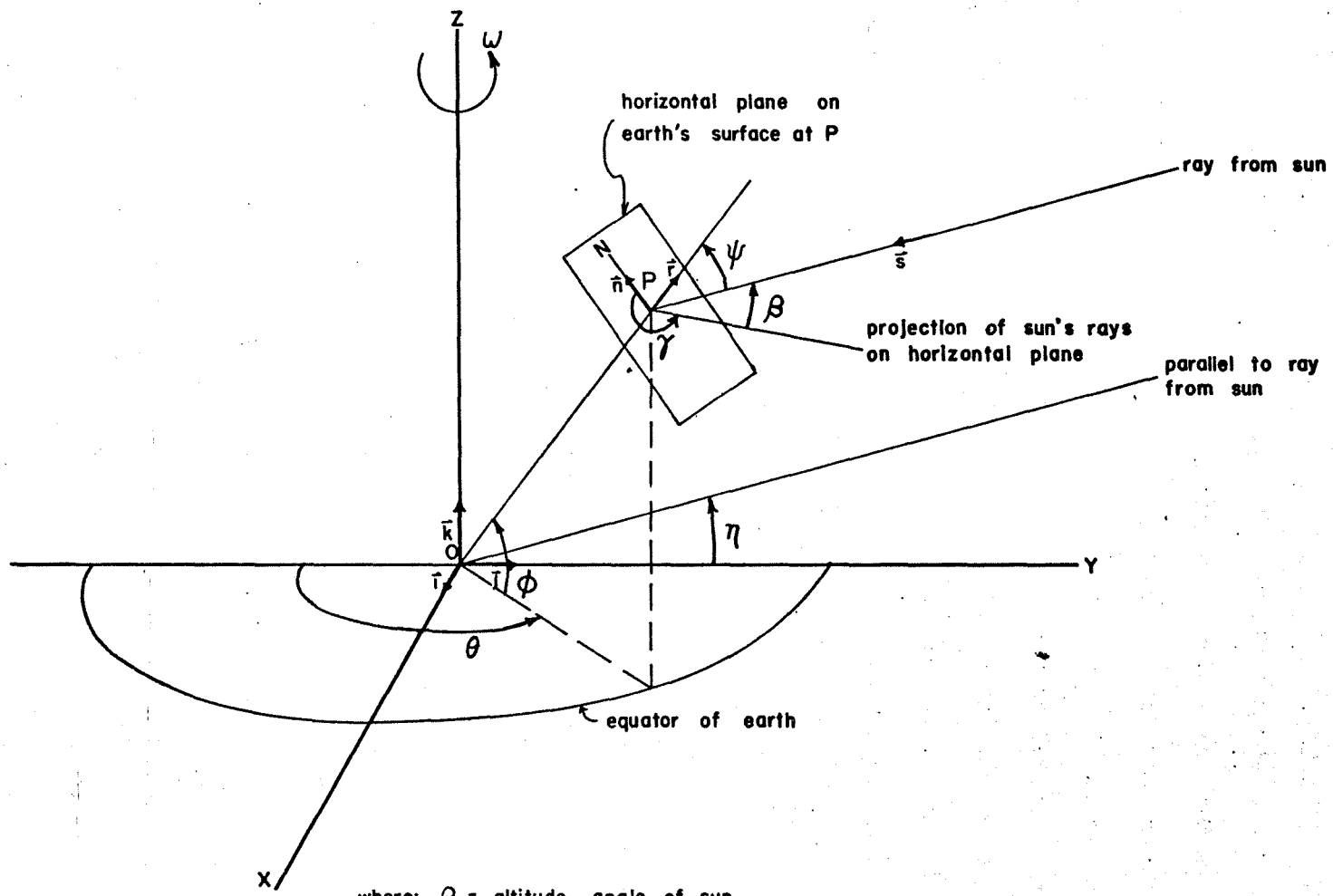
$$\beta = \arcsin(\sin\Phi \sin\eta - \cos\Phi \cos\theta \cos\eta) \qquad (5)$$

Now the vector $\vec{n}$ is

$$\vec{n} = -\sin\Phi \sin\theta\, \vec{i} + \sin\Phi \cos\theta\, \vec{j} + \cos\Phi\, \vec{k} \qquad (6)$$

Taking $\vec{n} \cdot \vec{s}$, since $\vec{n} \cdot \vec{r} = 0$, gives

$$\vec{n} \cdot \vec{s} = \sin\Phi \cos\theta \cos\eta + \cos\Phi \sin\eta \qquad (7)$$



where: β = altitude angle of sun

ψ = zenith angle of sun

γ = azimuth angle of sun

θ = hour angle

Figure B-1 Geometry for Solar Radiation

Also $\vec{n} \cdot \vec{s} = \cos \Upsilon \cos \beta$ (8)

where: Υ = sun's azimuth angle.

Therefore,

$$\Upsilon = \arccos \left[\sec \beta (\cos \Phi \sin \eta + \sin \Phi \cos \theta \cos \eta) \right] \quad (9)$$

Thus the sun's altitude and azimuth angles are determined as a function of latitude, Φ , solar declination angle, η , and time angle, θ.

B-2 Solar Declination Angle and Time Angle

The solar declination angle, η , is given as a function of the day of the year, see Figure B-2. This variation was approximated by the following function, namely,

$$\eta = 0.410 \sin \left[\frac{\pi}{182.5} (D-80) \right] \quad (10)$$

where: D = day of the year, 1 to 365.

The time angle, θ, is denoted by

$$\theta = \frac{\pi}{12} (T_{solar}) \quad (11)$$

where

T_{solar} = solar time, hrs, see Section 2.2.

B-3 Angle of Surface to Sun's Rays

Consider a tilted plane surface at an angle, ξ , to a vertical surface at a point P on the surface of the earth, see Figure B-3. The unit normal to the tilted surface, $\vec{n}_s$, is at the angle ξ to the normal to the vertical surface which makes an angle, Υ - a, with respect to the projection of the sun's rays on a horizontal surface at point P. If a right-handed rectilinear coordinate system is defined at point P, such that the X-axis is parallel to the direction of the projection of the sun's ray, $\vec{s}$, on the horizontal plane and the Y-axis is parallel to the vertical plane, the X-Z planeis the horizontal plane. Let the unit

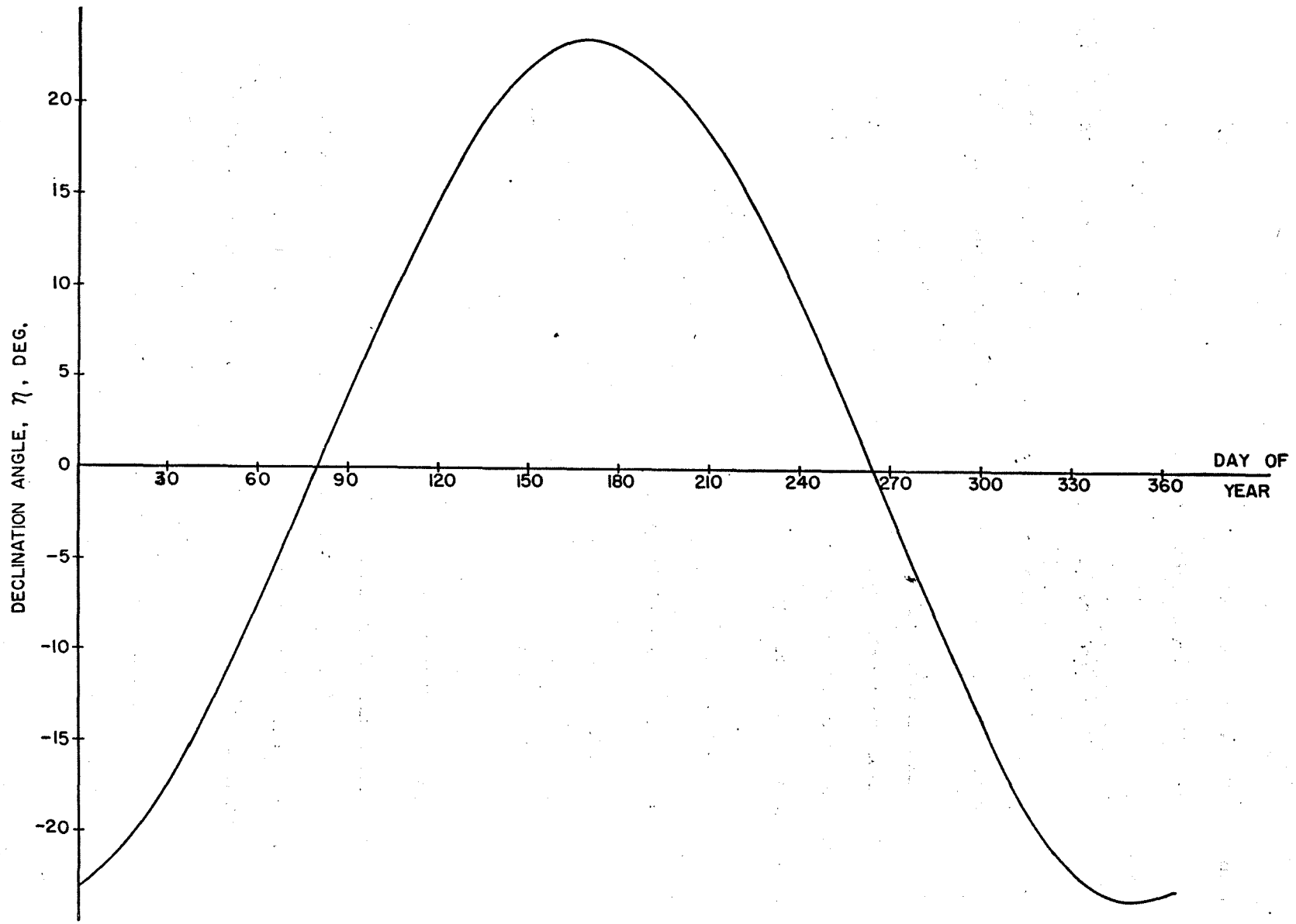


Figure B-2 Variation of Declination Angle, η, with the Day of the Year

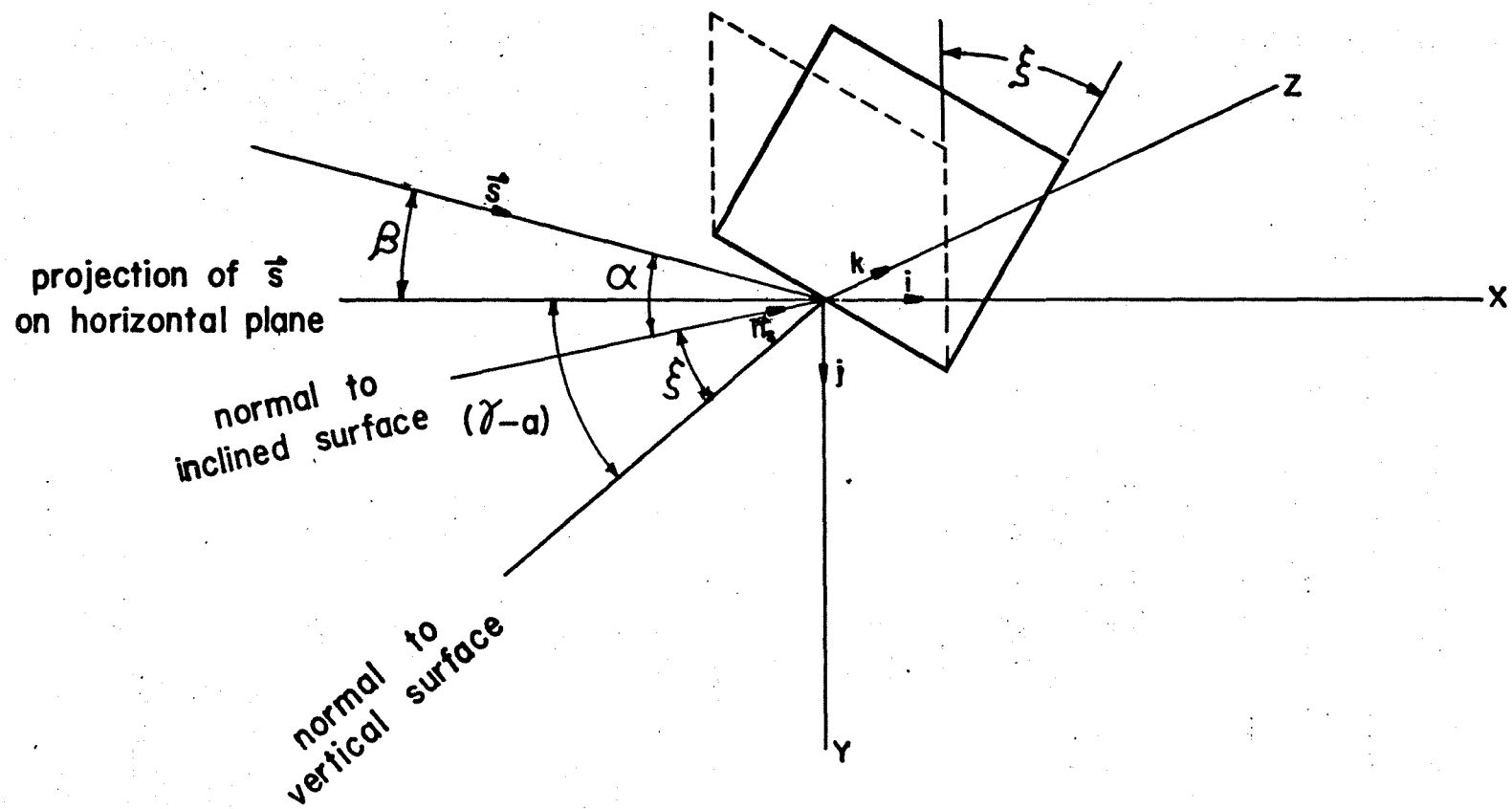


Figure B-3 Geometry for Tilted Surfaces

vectors $\vec{i}$, $\vec{j}$ and $\vec{k}$ be directed along the X, Y and Z axes, respectively. Then the unit normal to the tilted surface, $\vec{n}_s$, is

$$\vec{n}_s = \cos(\Upsilon - a) \cos \xi \, \vec{i} + \sin \xi \, \vec{j} + \sin(\Upsilon - a) \cos \xi \, \vec{k} \qquad (12)$$

where: a = azimuth of the normal to the vertical surface measured westward from north

Υ = azimuth of sun measured westward from north

with $\vec{s} = \cos \beta \, \vec{i} + \sin \beta \, \vec{j}$

Then

$$\vec{s} \cdot \vec{n}_s = \cos \beta \cos(\Upsilon - a) \cos \xi + \sin \beta \sin \xi \qquad (13)$$

but $$\vec{s} \cdot \vec{n}_s = \cos \alpha \qquad (14)$$

where:

α = angle between the normal to the tilted surface and the sun's rays

Therefore

$$\alpha = \arccos (\cos \beta \cos(\Upsilon - a) \cos \xi + \sin \beta \sin \xi) \qquad (15)$$

B-4 <u>Sunrise and Sunset Values of Hour Angle</u>

At sunrise, $\beta = 0$; then from equation (5) have

$$0 = \arcsin (\sin \Phi \sin \eta - \cos \Phi \cos \Theta_r \cos \eta)$$

or $$\Theta_r = \arccos (\tan \Phi \tan \eta) \qquad (16)$$

where: Θ_r = value of Θ at sunrise

However, the relation

$$-1 \leq \tan \Phi \tan \eta \leq 1$$

must hold.

Now the calculation of solar radiation is restricted to the northern hemisphere:

$$0 \leq \Phi \leq \frac{\pi}{2} \tag{17}$$

and, from Figure B-2, η varies as

$$-0.410 \leq \eta \leq 0.410 \tag{18}$$

Thus, to satisfy the restriction on the ϕ and η values, the ranges must be

$$\Phi + \eta \leq \frac{\pi}{2} \tag{19}$$

and

$$\Phi \leq \frac{\pi}{2} \tag{20}$$

Since η is a function of the day of the year, these restrictions indicated that there is a maximum value of latitude, Φ , that can be considered at each day of the year, see Figure 3-1.

The value of the hour angle for sunset, θ_s, is

$$\theta_s = 2\Pi - \theta_r \tag{21}$$

Thus, for $\theta_r \leq \theta \leq \theta_s$ there can be some form of solar radiation upon a surface as long as $0 \leq \beta \leq \frac{\pi}{2}$.

B-5 Intensity of Solar Radiation

The intensity of solar radiation that will be incident upon a surface is given by

$$I = I_{DIR} + I_{DIF} + I_{REF} \tag{22}$$

where: I_{DIR} = intensity of direct solar radiation

I_{DIF} = intensity of diffuse solar radiation

I_{REF} = intensity of solar radiation reflected from the ground and surrounding surfaces onto the surface

The assumption is made that the reflected solar radiation from the surroundings is negligible, $I_{REF} = 0$.

Thus

$$I = I_{DIR} + I_{DIF} \tag{23}$$

The direct solar radiation is given by

$$I_{DIR} = \begin{cases} I_{DN} \cos \alpha & 0 \leq \alpha \leq \pi/2 \\ 0 & \alpha > \frac{\pi}{2} \end{cases} \tag{24}$$

where: I_{DN} = intensity of direct normal solar radiation; i.e., the direct radiation on a surface normal to the sun's rays.

The intensity of the direct normal solar radiation, I_{DN}, is given as a function of the sun's altitude angle, β, (from Reference 6), see Figure B-4. The data are approximated by the relationships

$$I_{DN} = \begin{cases} 294\,(1-e^{-\frac{10}{\pi}\beta}) & \text{for clear air} \\ 200\,(1-e^{-\frac{7}{\pi}\beta}) & \text{for industrial air} \end{cases} \tag{25}$$

for $\beta > 0$.

The intensity of the diffuse solar radiation is assumed to be defined by

$$I_{DIF} = I_{DIF,V} + (I_{DIF,H} - I_{DIF,V}) \sin \xi \tag{26}$$

where: $I_{DIF,V}$ = intensity of diffuse solar radiation on a vertical surface

$I_{DIF,H}$ = intensity of diffuse solar radiation on a horizontal surface.

The ratio of the intensity of diffuse solar radiation on a vertical surface to the intensity of diffuse solar radiation on a horizontal surface is given as a function of the cosine of the angle between the normal to the vertical surface and the sun's rays (from Reference 7), see Figure B-5.

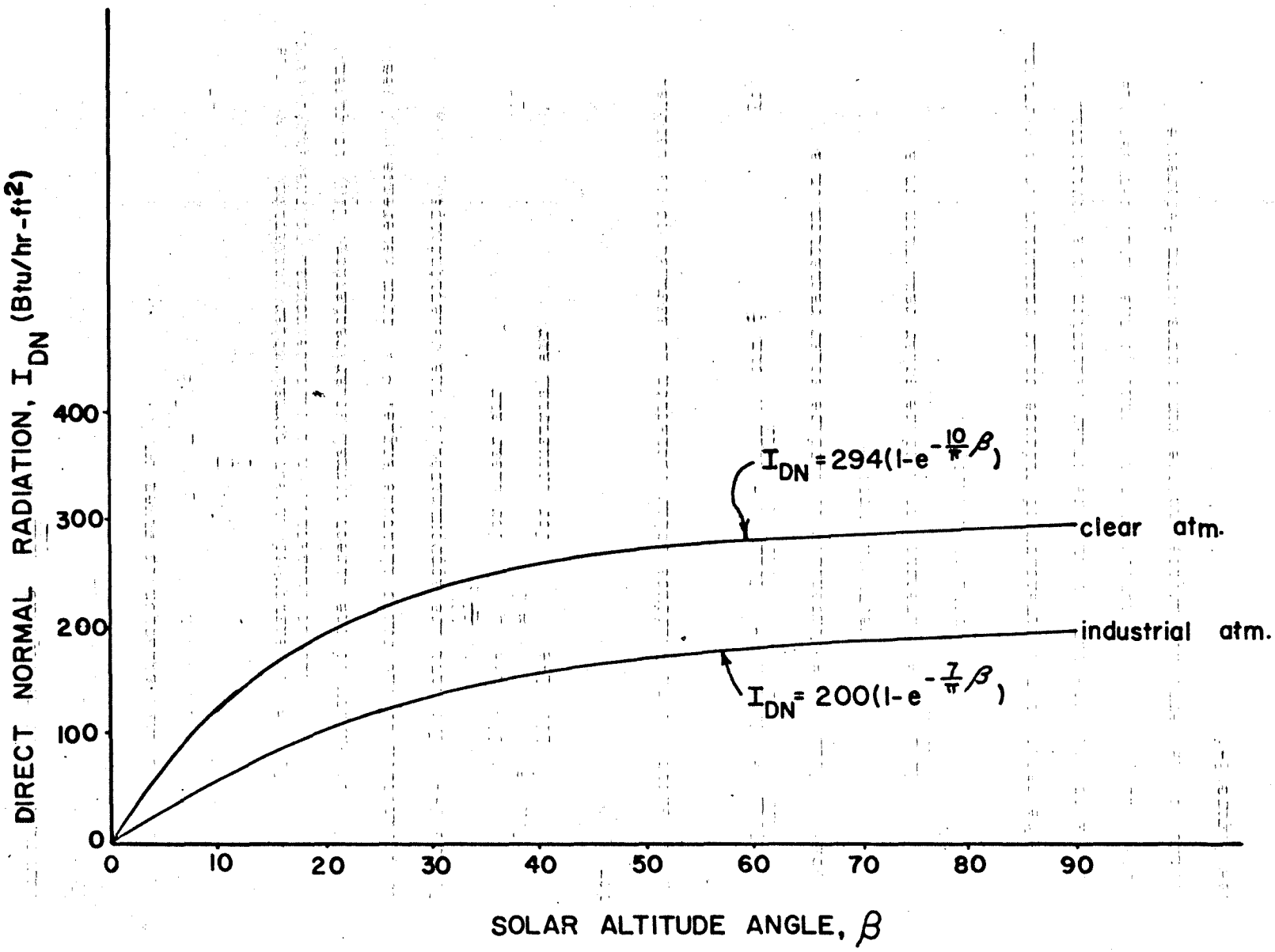


Figure B-4 Direct Normal Radiation as a Function of β

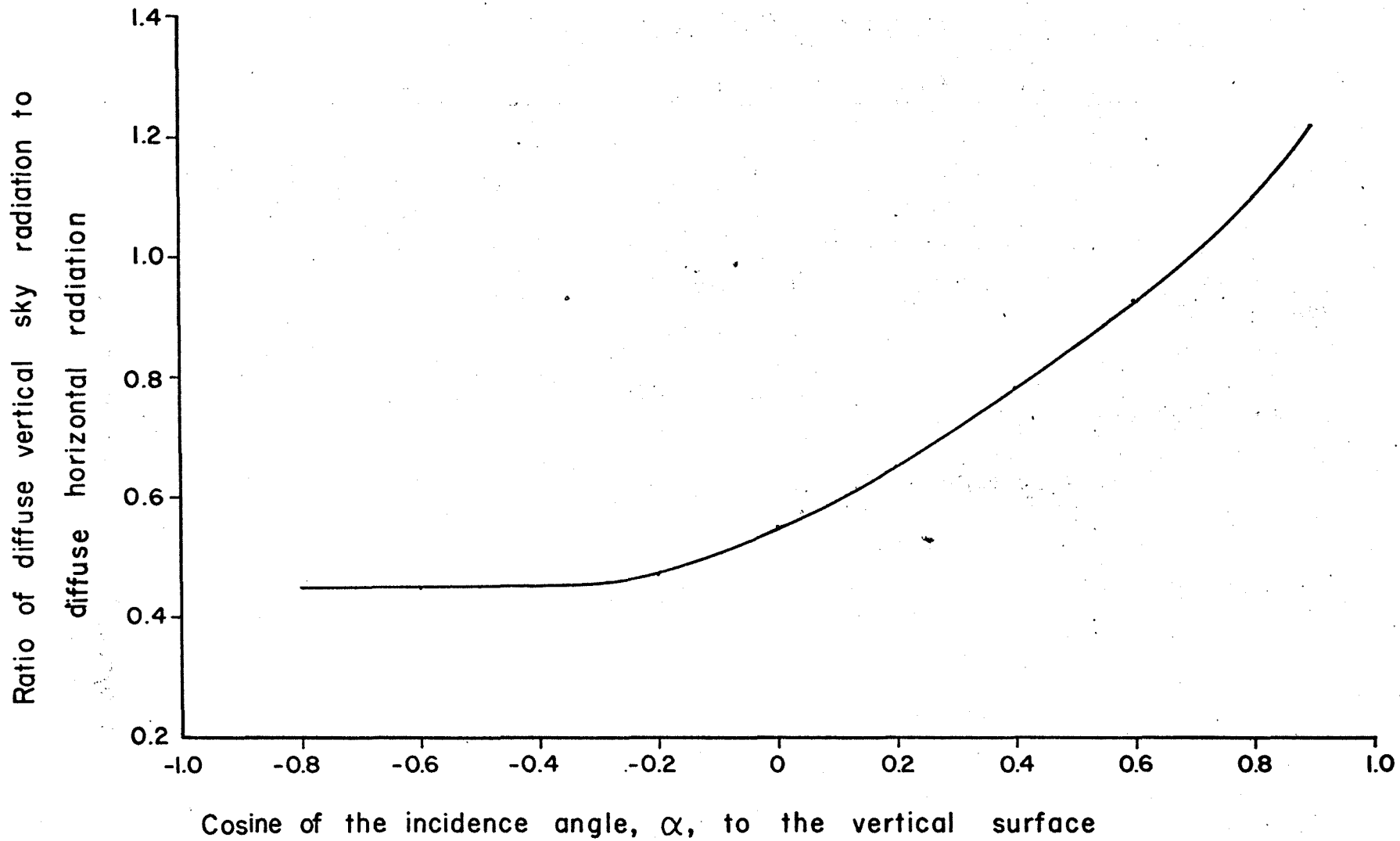


Figure B-5 Ratio of Diffuse Sky Radiation Incident Upon a Vertical Surface to that Incident Upon a Horizontal Surface During Clear Days (Ref. 7)

The results are approximated by

$$\frac{I_{DIF,V}}{I_{DIF,H}} = \begin{cases} 0.44 & \text{for } \cos\beta \cos(\Upsilon - a) \leq -0.4 \\ 0.625\,[\cos\beta \cos(\Upsilon - a)]^2 + 0.525 \cos\beta \cos(\Upsilon - a) + 0.55 & \text{for } -0.4 < \cos\beta \cos(\Upsilon - a) < 0 \\ 0.35\,[\cos\beta \cos(\Upsilon - a)]^2 + 0.45 \cos\beta \cos(\Upsilon - a) + 0.55 & \text{for } \cos\beta \cos(\Upsilon - a) \geq 0 \end{cases} \quad (27)$$

Then

$$I_{DIF} = I_{DIF,H}\,[(1 - \sin\xi)\, f(\beta, \Upsilon - a) + \sin\xi] \quad (28)$$

The ratio of the total intensity of solar radiation, I_{TH}, on a horizontal surface, to the intensity of diffuse solar radiation on a horizontal surface, $I_{DIF,H}$ is given as a function of the direct normal solar radiation intensity (from Reference 8), see Figure B-6. The relationship can be approximated by

$$\frac{I_{TH}}{I_{DIF,H}} = 0.667 \times 10^{-6} (I_{DN})^3 - 1.5 \times 10^{-4} (I_{DN})^2 + 0.0183 (I_{DN}) + 1 \quad (29)$$

It may be assumed that

$$I_{TH} = I_{DIR,H} + I_{DIF,H}$$

$$= I_{DN} \sin\beta + I_{DIF,H} \quad (30)$$

Therefore,

$$I_{DIF,H} = \frac{I_{DN} \sin\beta}{\frac{I_{TH}}{I_{DIF,H}} - 1} \quad (31)$$

Combining equation (31) and equation (28) gives

$$I_{DIF} = \frac{\sin\beta\,[f(\beta, \Upsilon - a)\,(1 - \sin\xi) + \sin\xi]}{0.667 \times 10^{-6} (I_{DN})^2 - 1.5 \times 10^{-4} (I_{DN}) + 0.0183} \quad (32)$$

with total radiation on a surface given by equation (23).

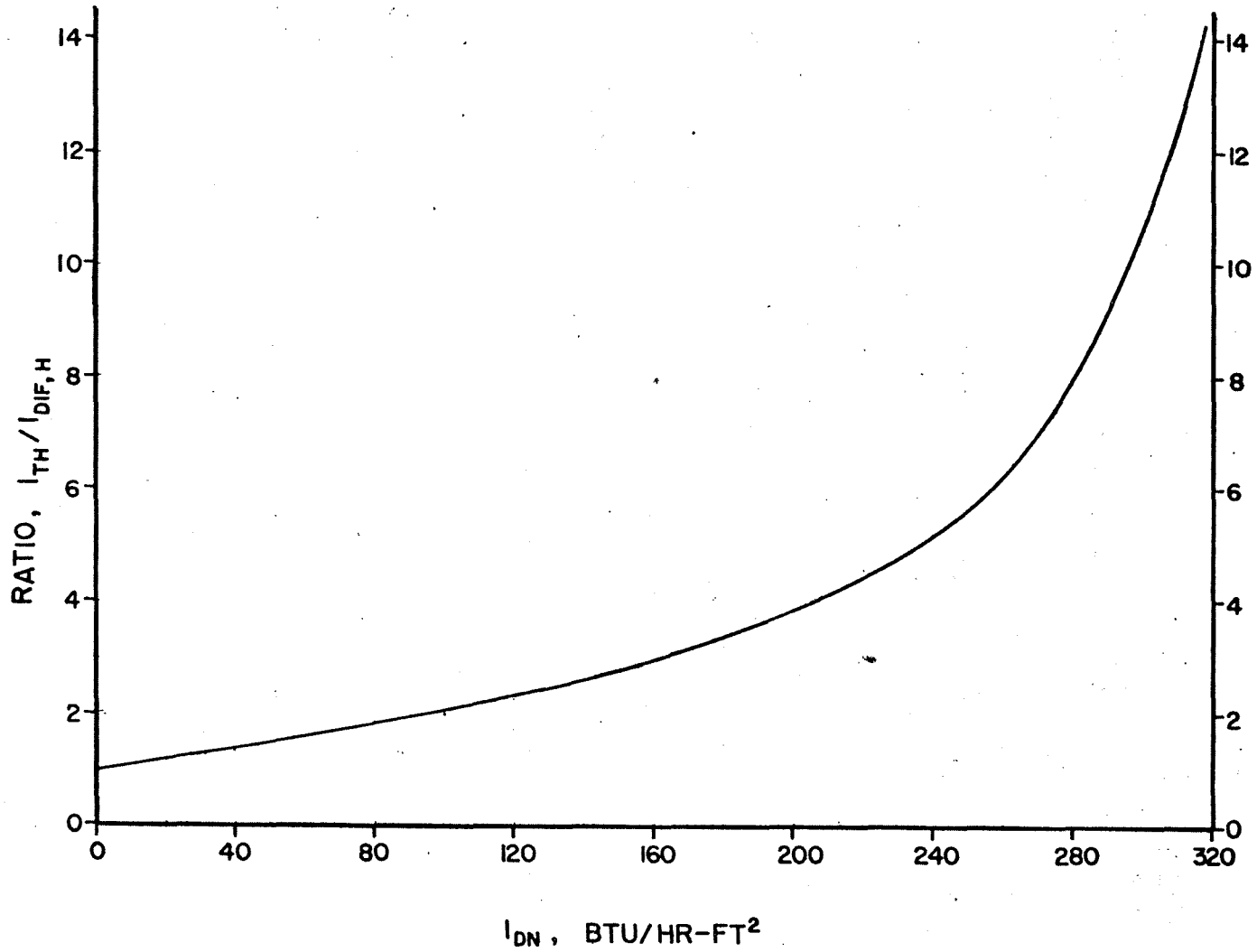


Figure B-6 Ratio of Total to Diffuse Solar Radiation on a Horizontal Surface vs Direct Normal Radiation, I_{DN} (Ref. 8)

APPENDIX C

BOUNDARY ENERGY TRANSFER AND NODAL TEMPERATURE COEFFICIENTS

Heat transfer by conduction through the shelter boundaries is determined by the temperature of each boundary inner surface. To calculate these temperatures, the temperature profile through each boundary is determined by the solution of a set of implicit finite-difference equations. Since each boundary may be multi-layered (up to 5 layers), the nodal point coefficients must be determined individually for each layer.

For this solution, a layer is divided into slabs δX thick. A temperature nodal point is assigned to the node of each slab; for the interior slabs, this point is at the midpoint of each slab, and for the innermost and outermost slabs, there is another point at the surface of the slab. If the boundary under analysis is multi-layered, a similar nodal point array accompanies each layer.

Nodal point temperatures are determined by the appropriate heat transfer equation at each nodal point. There are four basic heat balances that can occur at a node; the one to be used depends on the position of the node in question. These four positions are (1) at the inner surface of the boundary; (2) in the interior of any layer of the boundary; (3) at an interface between layers of the boundary; and (4) at the exterior surface of the boundary, see Figure C-1.

Position 1 - at the inner surface of a boundary. The heat transfer in this case is by convection with the shelter air and by conduction

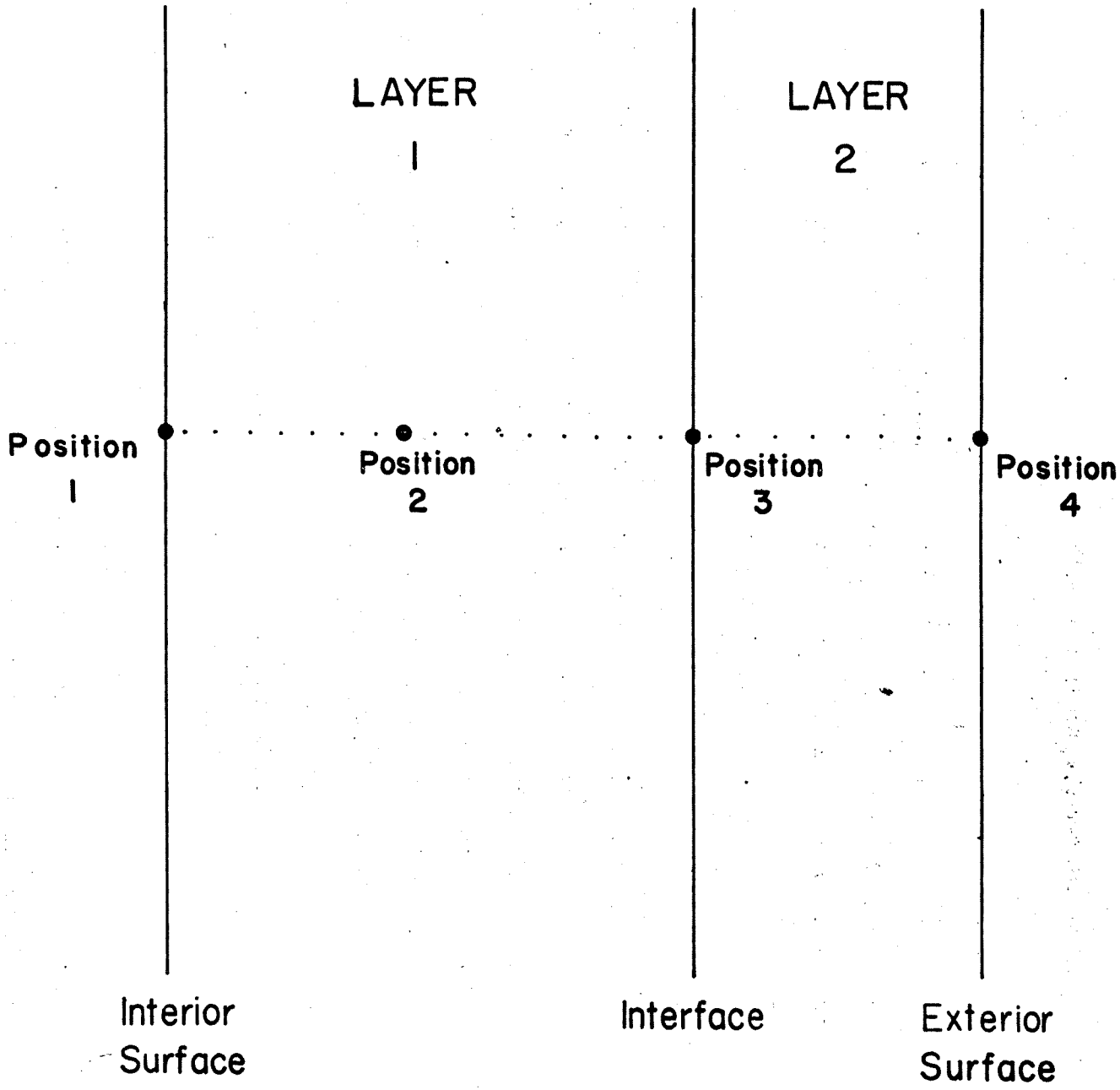


Figure C-1 Various Positions of Boundary Nodal Points

with the next slab in the layer. Heat transfer due to moisture condensation may also be present, see Appendix D. The general heat balance for deriving the various nodal point temperature equations is

$$\begin{bmatrix}\text{energy entering slab n} \\ \text{from preceding slab (n-1)}\end{bmatrix} - \begin{bmatrix}\text{energy leaving slab n} \\ \text{to succeeding slab (n+1)}\end{bmatrix} = \begin{matrix}\text{energy stored} \\ \text{in slab n}\end{matrix}$$

For position 1, the equation becomes:

$$q_{condensation} + q_{convection} - q_{conduction} = q_{stored} \qquad (1)$$

or $$C + h_i (T_{db,s} - T_n) - \frac{k}{\delta x}(T_n - T_{n+1}) = \frac{\rho C_p \delta x}{2 \delta \tau}(T_n - T_n') \qquad (2)$$

where C = condensation term, see Appendix D.

h_i = interior film heat-transfer coefficient, Btu/hr-ft^2-°F

$T_{db,s}$ = dry-bulb temperature of shelter, °F

T_n = temperature of node n, °F

k = thermal conductivity of layer material, Btu/hr-ft -°F

δx = thickness of slab in layer, ft.

T_{n+1} = temperature of node (n + 1), °F

ρ = density of layer material, lb/ft^3

C_p = specific heat of layer material, Btu/lb

$\delta \tau$ = time increment, hr.

T_n' = temperature of node n in preceding time increment, °F.

The matrix solution of simultaneous equations requires that the coefficients of the nodal temperatures are dimensionless. Therefore, the transformed energy balance for the inner surface nodal point is

$$\left(1.0 + \frac{k}{h_i \delta x} + \frac{\rho c_p \delta x}{2 h_i \delta \tau}\right) T_n - \left(\frac{k}{h \delta x}\right) T_{n+1} = \frac{\rho c_p \delta x}{2 h_i \delta \tau} T_n' + T_{db,s} + \frac{C}{h_i} \qquad (3)$$

which in matrix element notation is

$$a_{nn}T_n + a_{n,n+1}\,T_{n+1} = b_n \tag{4}$$

or, since the inner surface nodal point is indexed 1,

$$a_{11}\,T_1 + a_{12}\,T_2 = b_1 \tag{5}$$

<u>Position 2</u> - in the interior of any layer of the boundary. In this case, conduction into and out of slab n is the only heat transfer. Therefore, the energy balance becomes

$$\frac{k}{\delta x}(T_{n-1} - T_n) - \frac{k}{\delta x}(T_n - T_{n+1}) = \frac{\rho c_p \delta x}{\delta \tau}(T_n - T_n') \tag{6}$$

where T_{n-1} = temperature of node (n - 1), °F

This becomes, in dimensionless quantities,

$$-T_{n-1} + \left(\frac{(\delta x)^2 \rho c_p}{k\,\delta \tau} + 2\right) T_n - T_{n+1} = \frac{\rho c_p (\delta x)^2}{k \delta \tau}\, T_n' \tag{7}$$

which is of the form

$$a_{n,n-1}\,T_{n-1} + a_{n,n}\,T_n + a_{n,n+1}\,T_{n+1} = b_n \tag{8}$$

<u>Position 3</u> - at an interface between layers (m, and (m+1)) of a boundary. Again, the only heat transfer is conduction, but since the successive layers will have different thermal properties, the energy balance is:

$$\frac{k_m}{\delta x_m}(T_{n-1} - T_n) - \frac{k_{m+1}}{\delta x_{m+1}}(T_n - T_{n+1}) = \left(\frac{\rho_m c_{p,m}\,\delta x_m}{2} + \frac{\rho_{m+1} c_{p,m+1}\,\delta x_{m+1}}{2}\right)\left(\frac{T_n - T_n'}{\delta \tau}\right) \tag{9}$$

or, in dimensionless form,

$$-T_{n-1} + \left(1 + \frac{k_{m+1}\delta x_m}{k_m \delta x_{m+1}} + \frac{\rho_m c_{pm}(\delta x_m)^2}{2\,k_m\,\delta \tau} + \frac{\rho_{m+1} c_{pm+1}\,\delta x_m\,\delta x_{m+1}}{2\,k_m\,\delta \tau}\right) T_n$$

$$+ \left(-\frac{k_{m+1}\delta x_m}{k_m \delta x_{m+1}}\right) T_{n+1} = \left(\frac{\rho_m c_{p_m}(\delta x_m)^2 + \rho_{m+1} c_{p_{m+1}}\,\delta x_m \delta x_{m+1}}{2\,k_m\,\delta \tau}\right) T_n' \tag{10}$$

which is of the form:

$$a_{n,n-1}\, T_{n-1} + a_{n,n}\, T_n + a_{n,n+1}\, T_{n+1} = b_n \qquad (11)$$

Position 4 - at the exterior surface of the boundary. This case has several variations, depending on whether the external surface boundary is exposed to either soil or air.

If the boundary is backed by soil, the only mode of heat transfer will be conduction. The only difference between position 4 and position 2 is that the unknown temperatures T_{n+1} in equation (7) is replaced by the known temperature of the soil, T_{soil}, and this term, being known, becomes part of the b coefficient:

$$T_{n-1} + \left(\frac{\rho c_p (\delta x)^2}{k\,\delta\tau} + 2\right) T_n = \frac{\rho c_p (\delta x)^2}{k\,\delta\tau}\, T_n' + T_{soil} \qquad (12)$$

If the backing of the wall is ambient air, convection enters as well as solar radiation. The energy balance is

$$\frac{k}{\delta x}(T_{n-1} - T_n) + q_{solar} - h_o (T_n - T_a) = \frac{\rho c_p\, \delta x}{2\,\delta\tau}(T_n - T_n') \qquad (13)$$

where q_{solar} = solar radiation load on boundary, Btu/hr.

h_o = exterior film heat transfer coefficient, Btu/hr-ft^2-°F

T_a = dry-bulb temperature of ambient air, °F

In dimensionless form,

$$\left(-\frac{k}{h_o \delta x}\right) T_{n-1} + \left[\frac{k}{h_o \delta x} + 1 + \frac{\rho c_p \delta x}{h_o \delta\tau}\right] T_n = \frac{q_{solar}}{h_o} + T_a + \frac{\rho c_p \delta x}{2\delta\tau h_o}\, T_n' \qquad (14)$$

Both equations (12) and (14) are of the form

$$a_{n,n-1}\, T_{n-1} + a_{n,n}\, T_n = b_n \qquad (15)$$

If the wall is backed by interior air, $q_{solar} = 0$, and T_a is the average of the shelter temperature and the ambient temperature.

After all coefficients of all nodal points in a boundary have been evaluated, the equations are solved simultaneously using a Gauss-Jordan method of matrix inversion. Convection transfer through a boundary is then computed as

$$q_b = h_i (T_{db,s} - T_1) \quad , \tag{16}$$

where T_1 = temperature of the inner surface nodal point and the total boundary heat loss is

$$Q_b = \sum_{walls} q_b \tag{17}$$

APPENDIX D

MOISTURE CONDENSATION

The process of moisture condensing on, or re-evaporating from, a surface involves both a mass and an energy transfer. The analysis used in this study parallels that of Jakob[9].

The following differential equations may be set up for moving fluids, relating thermal conduction and mechanical diffusion:

$$\frac{\partial T}{\partial t} + v_x \frac{\partial T}{\partial x} + v_y \frac{\partial T}{\partial y} + v_z \frac{\partial T}{\partial z} = \alpha \left(\frac{\partial^2 T}{\partial x^2} + \frac{\partial^2 T}{\partial y^2} + \frac{\partial^2 T}{\partial z^2}\right) \qquad (1)$$

and

$$\frac{\partial p}{\partial t} + v_x \frac{\partial p}{\partial x} + v_y \frac{\partial p}{\partial y} + v_z \frac{\partial p}{z} = \delta \left(\frac{\partial^2 p}{\partial x^2} + \frac{\partial^2 p}{\partial y^2} + \frac{\partial^2 p}{\partial z^2}\right) \qquad (2)$$

where T = absolute temperature, °F
v = velocity, ft/hr
p = partial pressure of water vapor, lb/ft^2
α = thermal diffusivity, ft^2/hr
δ = mechanical diffusivity, ft^2/hr

Newton's Law yields

$$q'' = -k \frac{dt}{dn} \qquad (3)$$

and Fick's Law gives

$$\dot{m}'' = \delta \frac{dc}{dn} \qquad (4)$$

where q'' = rate of heat flow per unit area, Btu/ft^2-hr
$\dot{m}''$ = rate of mass flow per unit area, lb/ft^2-hr
n = direction of heat and mass flow, ft
k = thermal conductivity of the medium, Btu/hr-ft-°F
c = concentration, lb/ft^3

Define $m = m_v + m_a$ (5)

where m_v = mass of water vapor in shelter volume, lb

m_a = mass of dry air in shelter volume, lb

Define $\rho = \frac{m}{V} = \frac{m_v}{V} + \frac{m_a}{V} = \rho_v + \rho_a$ (6)

where ρ = density, lb/ft^3

V = volume of shelter, ft^3

Define $W = \frac{m_v}{m_a}$ (7)

Define c_v = concentration of vapor in dry air (assumed to) $= \rho_v$

c_a = concentration of dry air in water vapor (assumed to) $= \rho_a$

Now, from (4)

$$\dot{m}_v = -\delta \frac{dc_v}{dn} = -\delta \frac{d\rho_v}{dn} = -\delta \frac{d\left(\frac{m_v}{V}\right)}{dn}$$

$$= -\frac{\delta}{V} m_a \frac{d\left(\frac{m_v}{m_a}\right)}{dn} = -\delta\left(\frac{m_a}{V}\right) \frac{dW}{dn}$$

$$\dot{m}_v = -\delta \rho_a \frac{dW}{dn} \quad (8)$$

From (3)

$$\int_0^{\Delta x_T} q \, dn = -\int_{T_o}^{T_s} k \, dT \quad (9)$$

where Δx_T = thermal boundary layer thickness, ft.

T_o = temperature of the environment, °R

T_s = temperature of the boundary surface, °R

which leads to

$$q = \frac{k}{\Delta x_T} (T_o - T_s) \quad (10)$$

Similarly, equation (8) leads to

$$\dot{m}_v = \frac{\delta \rho_a}{\Delta x_w} (W_o - W_s) \quad (11)$$

where Δx_w = mechanical boundary layer thickness, ft.

W_o = humidity ratio of shelter environment, lb_w/lb_a

and W_s = humidity ratio at boundary temperature, lb_w/lb_a

Parallel expression to equations (10) and (11) are

$$q = h\,(T_o - T_s) \tag{12}$$

and

$$\dot{m}_v = \rho_a b\,(W_o - W_s) \tag{13}$$

where b = a coefficient of mass transfer, which must be evaluated.

A comparison of equation (10) with (12), and (11) with (13) shows

$$h = \frac{k}{\Delta x_T} \tag{14}$$

and

$$b = \frac{\delta}{\Delta x_w} \tag{15}$$

It is assumed that the thermal and mechanical boundary layer thickness are very nearly equal:

$$\Delta x_T = \Delta x_w \tag{16}$$

Therefore:

$$\frac{h}{b} = \frac{k}{\delta} \tag{17}$$

or

$$\frac{h}{\rho_a c_p b} = \frac{k}{\rho_a c_p \delta} = \frac{\alpha}{\delta} \tag{18}$$

where α = thermal diffusivity $= \dfrac{k}{\rho_a c_p}$

Therefore,

$$b = \frac{h}{\rho_a c_p}\left(\frac{\delta}{\alpha}\right) \tag{19}$$

Now, for water diffusing into air, $\frac{\alpha}{\delta} = 0.917$ (Ref. 9)

since $\alpha = 0.070\ ft^2/hr$ for air

and $\delta = 0.765$ for water vapor

at 0°C and 760 mm Hg.

Therefore $b = \frac{h}{\rho_a c_p} \left(\frac{1}{0.917}\right)$

$$= 1.09 \left(\frac{h}{\rho_a c_p}\right) \tag{20}$$

and $\dot{m}_v = \rho_a b \, (W_o - W_s)$

$$= 1.09 \left(\frac{h}{\rho_a c_p}\right) (W_o - W_s) \tag{21}$$

where c_p = specific heat of air-water vapor mixture

$\approx$ 0.24 Btu/lb-°F

Since $q = \dot{m}_v \lambda$ (22)

where λ = heat of condensation, Btu/lb

$$q_{condensation} = \frac{1.09 \lambda h}{\rho_a c_p} (W_o - W_s) \tag{23}$$

Now, since $W = 0.622 \frac{p'}{p_b - p'}$ (24)

where W = humidity ratio

p' = partial pressure of water vapor,

p_b = barometric pressure,

we may approximate

$$W_o - W_s = 0.622 \left(\frac{p_o}{p_b - p_o} - \frac{p_s}{p_b - p_s}\right) \tag{25}$$

Therefore the heat transfer due to condensation is expressible by:

$$q_{condensation} = 2.825 \frac{\lambda h}{\rho_a} \left(\frac{p_o}{p_b - p_o} - \frac{p_s}{p_b - p_s}\right) \tag{26}$$

and condensation is determined to be present if $p_o > p_s$. This is the condensation term of equations (1) and (2) of Appendix C. Also, equation (26) expresses the heat transfer due to re-evaporation of the condensate, if the energy and mass transfer phenomena are assumed to be equivalent

in the two processes. In the case of evaporation, $p_s > p_o$ and the $q_{condensation}$ term is negative ($C < 0$). The value of ρ_a in equation (26) is assumed to be defined by

$$\rho_a = 3.25 \times 10^{-7} T^2 - 1.86 \times 10^{-4} T + 0.0863 \qquad (27)$$

where T = the average of the temperature of the boundary surface in question and the shelter dry-bulb temperature, °F.

APPENDIX E

ERROR INTRODUCED BY CONSIDERING THREE-DIMENSIONAL HEAT TRANSFER AS A ONE-DIMENSIONAL PHENOMENON

If a shelter boundary is curved, such as in a tunnel, the one-dimensional heat transfer calculations introduce errors because the heat flow is no longer one-dimensional. But the one-dimensional analysis is applicable to such situations. A comparison of the relative rates of heat transfer will determine the error of the application.

For a flat boundary, the heat transmitted from the inner surface to nodal point n is

$$q = -kA \frac{T_1 - T_n}{\Delta x} \tag{1}$$

where k = thermal conductivity of flat surface along a normal, $\frac{Btu}{hr\text{-}ft^2\text{-}°F}$

A = area of the boundary, ft^2

T_1 = temperature of inner surface of boundary, °F

T_n = temperature of nth nodal point, °F

Δx = distance along a normal between nodal points i and n, ft.

Heat transfer through a spherical layer of the boundary from the inner surface of the boundary to nodal point n is:

$$q = -k\,(4\pi r^2)\,\frac{dT}{dr} \tag{2}$$

which, for steady state, may be integrated to

$$q = k\,(4\pi)\,\frac{T_1 - T_n}{\frac{1}{r_1} - \frac{1}{r_n}} \tag{3}$$

where r_1 = radius of curvature of the inner surface of the boundary

r_n = radius of curvature to the nth nodal point

See Figure E-1.

This is equivalent to

$$q = \frac{1}{\beta} k A_m \frac{T_1 - T_n}{\Delta r} \tag{4}$$

where A_m = heat conductance area at the average radius

$$A_m = 4\pi \frac{(r_1 + r_n)^2}{2} \tag{5}$$

and

$$\beta = \frac{1}{2} + \frac{1}{4} \left(\frac{r_1}{r_n}\right) + \frac{1}{4} \left(\frac{r_n}{r_1}\right) \tag{6}$$

β represents the difference in calculating heat transfer using the two analyses; it represents the percent departure of the one-dimensional analysis from the three-dimensional analysis. Values of β as a function of $\frac{r_n}{r_1}$ are shown in Table V.

Using a similar analysis for cylindrical coordinates, the expression for β becomes

$$\beta = \frac{1}{2} \left(\frac{\frac{r_n}{r_1} + 1}{\frac{r_n}{r_1} - 1}\right) \ln \left(\frac{r_n}{r_1}\right) \tag{7}$$

and its variation with (r_n/r_1) is also given in Table V.

Now say a tunnel with a radius of ten feet were used as a shelter. Assume, too, that the boundary is soil-backed and therefore the maximum outermost nodal point is ten feet past the outer surface of the boundary.

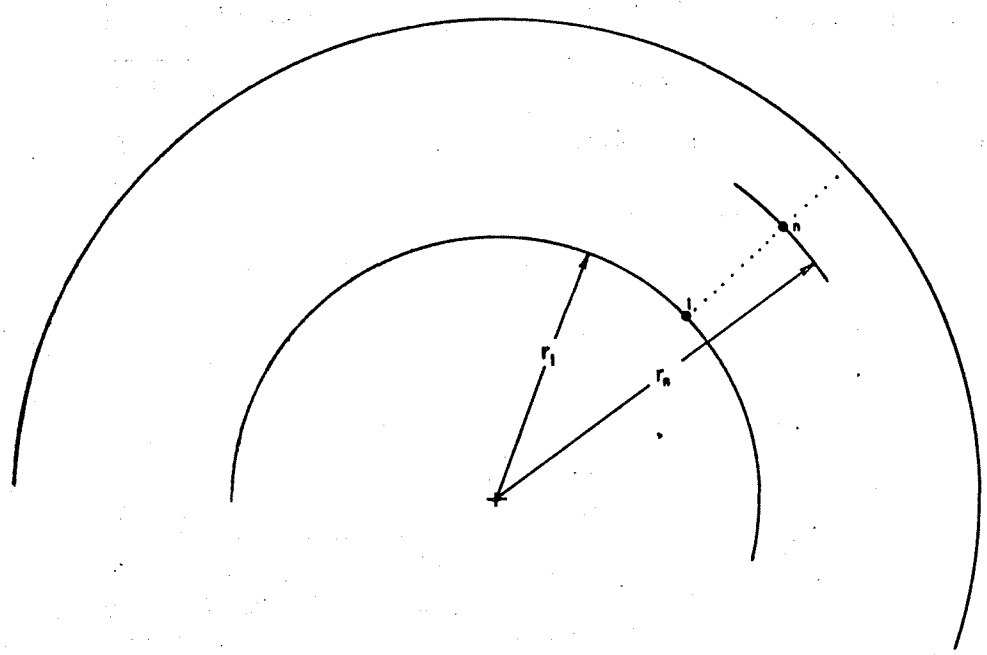


Figure E-1 Nodal Point Radii in a Cylindrical Shelter Used in Determining the β Error

TABLE V

ERRORS OF CONSIDERING THREE-DIMENSIONAL HEAT TRANSFER AS ONE-DIMENSIONAL

$\frac{r_n}{r_1}$	β(Cylindrical)	β (Spherical)
1.0	1.0	1.0
1.1	1.001	1.002
1.2	1.003	1.008
1.3	1.006	1.017
1.4	1.010	1.029
1.5	1.014	1.042
1.6	1.018	1.056
1.7	1.023	1.072
1.8	1.029	1.089
1.9	1.034	1.107
2.0	1.040	1.125
2.1	1.046	1.144
2.2	1.051	1.164
2.3	1.057	1.184
2.4	1.063	1.204
2.5	1.068	1.225

Therefore,

$$\frac{r_n}{r_1} = \frac{r_1 + \Delta p + 10}{r_1} = 2 + \frac{\Delta p}{10} \tag{8}$$

where p is the thickness of the boundary. A reasonable value of p would be 3 feet and thus the error in the heat flow due to using a one-dimensional analysis method of a three-dimensional analysis is 5.7% using the cylindrical surface analysis or 18.4% using the spherical surface analysis. (See Table V.) Generally, a tunnel designed as a mass shelter can be expected to have a radius greater than ten feet; therefore, the error introduced would be correspondingly less. Hence a shelter boundary that is curvilinear can be treated as a flat surface with an error given by equation (6) or (7).

APPENDIX F

ESTIMATION OF ERROR ASSOCIATED WITH CALCULATION OF AIR-CONDITIONING LOAD

The performance of an air-conditioning system is a function of the environmental conditions, the psychrometric state of the air entering the unit, the performance characteristics of the components comprising the system, the flow field in the unit and the characteristics of the heat sink and source reservoirs. Procedures are required to define an air-conditioning system for primarily cooling the air introduced into the shelter. The operating principles for such a unit can be based upon a large number of choices. However, in almost every choice, a coil will be utilized for cooling and dehumidifying the air. Therefore, the SHEP code has been constructed so as to require only the specification of the coil. It is assumed that once the coil has been defined, the designer can develop a system to produce the specified coil performance.

In particular, the coil is specified by denoting

1) a coil bypass factor,
2) an effective coil surface temperature, and
3) an air flow rate across the coil.

It is known that the coil bypass factor and effective coil surface temperature are a function of the thermal load, i.e., the psychrometric state and flow rate of the air through the coil. In the SHEP code, this load dependence is neglected (since performance is a function of the design of the entire system) and the bypass factor and effective coil surface temperature are assumed constant.*

*This procedure is a generalization of a coil selection procedure presented in "Fundamentals of Psychrometrics - Part II", T200-20, Carrier Air Conditioning Company, page 18.

The accuracy of this procedure has been checked by comparison with the performance data of an actual air-conditioning unit, see Table VI . It was found that neither the deduced bypass factor nor the deduced effective coil surface temperature are constant. However, if median values of the range of each of these parameters are used to calculate the capacity of the unit, this calculated unit capacity differs from the actual unit capacity by at most 37% and generally by less than 12%. This agreement is considered sufficient for the inclusion of this simplified specification for the air-conditioning equipment in the SHEP code.

TABLE VI

ESTIMATION OF ERROR ASSOCIATED WITH CALCULATION OF AIR CONDITIONING LOAD*

Air Temperatures at Evaporator				Deduced Effective Coil Surface Temperature (°F)	Deduced Bypass Factor	Evaporator Air Flow (cfm)	Actual Unit Capacity (Btu/hr)	Calculated Unit Capacity (Btu/hr)**	% Error in Calculated Unit Capacity
Entering Dry-Bulb (°F)	Entering Wet-Bulb (°F)	Leaving Dry-Bulb (°F)	Leaving Wet-Bulb (°F)						
113.1	82.2	72.5	66.6	60.7	0.227	630	40,900	52,200	+27.7
112.6	77.8	66.3	60.3	54.1	0.214	605	39,200	42,500	+8.4
102.1	83.1	70.9	66.4	54.1	0.347	637	44,600	59,500	+3.3
102.1	78.0	64.6	59.3	47.5	0.179	602	41,600	43,600	+4.8
102.3	72.1	59.0	54.1	48.7	0.190	602	35,400	31,450	-11.2
92.3	73.6	58.0	54.0	39.5	0.345	605	40,100	35,400	-11.7
91.8	66.6	51.7	47.4	43.3	0.156	605	34,200	21,800	-36.3

*Data from report, "Shelter Air Conditioning Unit", Final Report, OCD Work Unit 1425B, Carrier Air Conditioning Company, February, 1967, p. 24.

**Unit capacity calculated by the use of a constant bypass factor of 0.252 (median of deduced extreme values) and a constant effective coil surface temperature of 50°F (median of deduced extreme values).

APPENDIX G

TYPICAL THERMAL PROPERTIES AND DENSITIES OF BUILDING MATERIALS, SOILS, ETC.

BUILDING MATERIAL

		Thermal Conductivity CON (Btu/hr-ft-°F)	Specific Heat CP (Btu/lb-°F)	Density ROW (lb/ft^3)
I	Building Board			
	1. Asbestos-cement Board	0.33	0.270	120.00
	2. Gypsum or Plastic Board $\frac{3}{8}$"	0.10	0.270	50.00
	" " " $\frac{1}{2}$"	0.09	0.270	50.00
	3. Plywood	0.07	0.500	34.00
	4. Sheathing, Wood Fiber	0.03	0.500	20.00
	5. Wood Fiber Board	0.03	0.500	26.00
	6. Wood Fiber, hardboard type	0.12	0.500	65.00
II	Finish Flooring Materials			
	1. Cork tile - $\frac{1}{8}$"	0.03	0.485	15.60
	2. Terrazzo - 1"	1.04	0.250	150.00
III	Insulating Materials			
	A. Blanket & Batt			
	1. Cotton Fiber	0.02	0.362	0.8-2.0
	2. Mineral wool, fibrous form processed from rock, slag, or glass	0.03	0.30	0.5
		0.02	0.30	1.5-4.0
	3. Wood Fiber	0.02	0.30	3.2-3.6

	CON (Btu/hr-ft-°F)	CP (Btu/lb-°F)	ROW (lb/ft^3)
B. Board & Slabs			
1. Cellular Glass	0.03	0.185	9
2. Corkboard	0.02	0.485	6.5-8.0
	0.02		12
3. Glass Fiber	0.02	0.185	4-9
4. Expanded rubber (rigid)	0.02	0.339	4.5
5. Expanded polyurethane (thickness 1 in. and greater)	0.02	0.20-0.25	1.5-2.5
6. Expanded polystyrene extruded	0.02	0.30-0.35	1.9
molded beads	0.02	0.30-0.35	1.0
7. Mineral Wood with resin binder	0.02	0.30	15
C. Loose Fill			
1. Mineral wool (glass, slag or rock)	0.03	0.30	2.0-5.0
2. Perlite (expanded)	0.03	0.378	5.0-8.0
3. Sawdust or shavings	0.04	0.30	0.8-15
4. Silica Aerogel	0.01	0.205	7.6
5. Vermiculite (expanded)	0.04	0.30	7.0-8.2
	0.04	0.30	4.0-6.0
6. Wood Fiber, redwood, hemlock, or fir	0.02	0.30	2.0-3.5
IV Masonry Materials			
1. Cement Mortar	0.42	0.271	116.0
2. Gypsum-fiber concrete 87-1/2% gypsum, 12-1/2% wood chips	0.01	0.25	51.0

	CON (Btu/hr-ft-°F)	CP (Btu/lb-°F)	ROW (lb/ft^3)
3. Lightweight aggregates including: expanded shale, clay, or slate; expanded slags; cinders; pumice; perlite; vermiculite; also cellular concretes	0.43	0.20-0.25	120
	0.30	0.20-0.25	100
	0.21	0.20-0.25	80
	0.14	0.20-0.25	60
	0.10	0.20-0.25	40
	0.08	0.20-0.25	30
	0.06	0.20-0.25	20
4. Stucco	0.42	0.20-0.25	116
V Masonry Units			
1. Brick, common	0.42	0.20	120
2. Brick, face	0.75	0.20	130
3. Clay tile, hollow			
1 cell deep 3 in.	0.31	0.15	30
2 cells deep 6 in.	0.33	0.15	30
2 cells deep 8 in.	0.36	0.15	30
2 cells deep 10 in.	0.38	0.15	30
3 cells deep 12 in.	0.40	0.15	30
4. Concrete blocks, rectangular core Sand and gravel aggregate	0.15	0.25	30
5. Stone, lime or sand	1.04	0.22	150
VI Plastering Materials			
1. Cement Plaster, sand aggregate	0.42	0.20	116
2. Gypsum Plaster			
Perlite aggregate	0.12	0.20	45
Sand aggregate	0.47	0.20	105
Vermiculite aggregate	0.01	0.20	45

	CON (Btu/hr-ft-°F)	CP (Btu/lb-°F)	ROW (lb/ft^3)
VII Roofing			
1. Asbestos-cement shingles	0.40	0.20	120
2. Asphalt roll roofing	0.54	0.20	70
3. Asphalt shingles	0.19	0.20	70
VIII Siding Materials (on flat surfaces)			
1. Shingles - asbestos-cement	0.40	0.20	120
2. Siding			
asbestos-cement - $\frac{1}{4}$"	0.10	0.20	120
asphalt roll siding	0.54	0.20	120
3. Architectural glass	0.83	0.15-0.20	150-175
IX Woods			
1. Maple, oak, and similar hardwoods	0.09	0.50	45
2. Fir, pine and similar softwoods	0.07	0.50	32

CONFIGURATION

	Thermal Conductivity / Unit Distance CON/DX (Btu/hr-ft-°F)	Specific Heat CP (Btu/lb-°F)	Density ROW (lb/ft^3)
I Vertical Space	1.03	0.24	0.075
II Horizontal Space			
1. Heat flow up	1.18	0.24	0.075
2. Heat flow down	1.01	0.24	0.075
III 45° Inclined Space			
1. Heat flow up	1.11	0.24	0.075
2. Heat flow down	1.13	0.24	0.075

SOIL

		Thermal Conductivity CON (Btu/hr-ft-°F)	Specific Heat CP (Btu/lb-°F)	Density ROW (lb/ft^3)
I	Crushed quartz	0.96	0.188	100.00
II	Graded sand	0.83	0.210	100.00
III	Gravel	0.75	0.200	110.00
IV	Crushed feldspar	0.50	0.190	100.00
V	Crushed granite	0.46	0.230	100.00
VI	Sandy loam	0.54	0.210	110.00
VII	Crushed trap rock	0.42	0.195	100.00
VIII	Sand	0.37	0.210	100.00
IX	Clay	0.33	0.220	100.00
X	Silt loam	0.42	0.220	90.00
XI	Silty clay loam	0.42	0.200	90.00

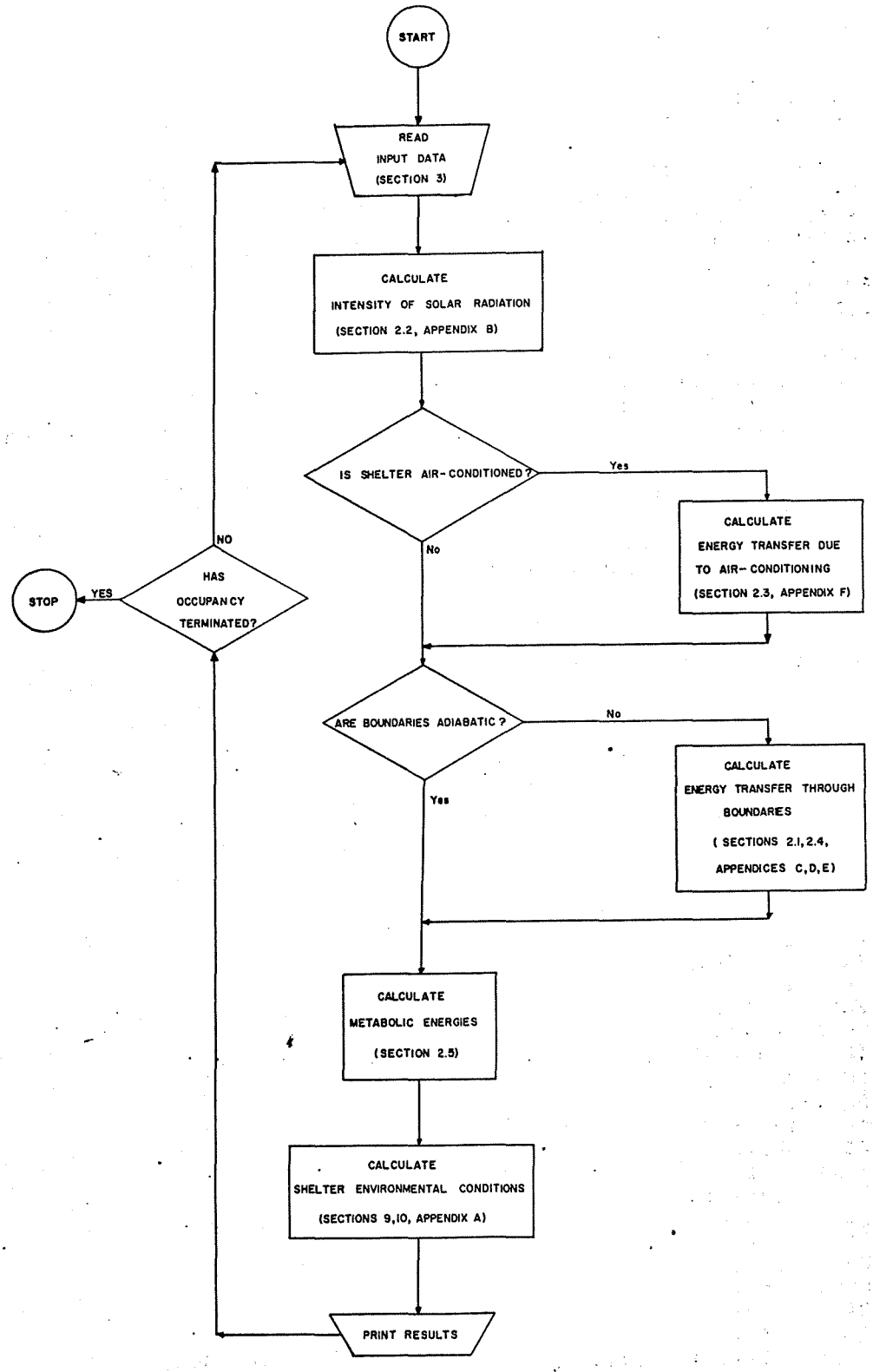
BOUNDARY ORIENTATION

		Direction of Heat Flow	Film Heat-Transfer Coefficient HI, HO (Btu/hr-ft^2-°F)
I	Vertical	Into or out of shelter	1.46
II	Horizontal (ceiling)	Into shelter	1.08
		Out of shelter	1.63
III	Horizontal (floor)	Into shelter	1.63
		Out of shelter	1.08

APPENDIX H

SHEP CODE, MODIFICATION 3

FLOW CHART AND LISTING


START
READ
INPUT DATA
(SECTION 3)
CALCULATE
INTENSITY OF SOLAR RADIATION
(SECTION 2.2, APPENDIX B)
IS SHELTER AIR-CONDITIONED?
Yes
No
CALCULATE
ENERGY TRANSFER DUE
TO AIR-CONDITIONING
(SECTION 2.3, APPENDIX F)
ARE BOUNDARIES ADIABATIC?
No
Yes
CALCULATE
ENERGY TRANSFER THROUGH
BOUNDARIES
(SECTIONS 2.1, 2.4,
APPENDICES C, D, E)
CALCULATE
METABOLIC ENERGIES
(SECTION 2.5)
CALCULATE
SHELTER ENVIRONMENTAL CONDITIONS
(SECTIONS 9, 10, APPENDIX A)
PRINT RESULTS
HAS
OCCUPANCY
TERMINATED?
NO
YES
STOP

```
      PROGRAM SHEP
C
C SHELTER ENVIRONMENTAL PREDICTION CODE  (SHEP--MOD. 3)
C GENERAL AMERICAN RESEARCH DIVISION
C GENERAL AMERICAN TRANSPORTATION CORPORATION
C
C THIS CODE CALCULATES THE RESPONSE OF A SHELTER TO TIME-VARYING THERMAL LOADS
C AND VENTILATION INLET PSYCHROMETRIC CONDITIONS.  THE CODE ACCOMMODATES SOLAR
C RADIATION, BOUNDARY SURFACE HEAT TRANSFER, MOISTURE CONDENSATION ON THE
C BOUNDARIES, EQUIPMENT AND LIGHTING LOADS, AND AIR-CONDITIONING.  THE USER
C MANUAL EXPLAINS THE VARIOUS FEATURES OF THE CODE, PRESENTS THE INPUT AND
C OUTPUT FORMATS, GIVES REPRESENTATIVE INPUT DATA VALUES, AND INCLUDES AN
C APPLICATION OF THE CODE TO A TYPICAL SHELTER STRUCTURE.
C
      COMMON/MATRIX/AINV(40,40,20)
      DIMENSION TWALL(40,20),A(40,40),INDEX(40,2),T(40)
      DIMENSION EQTIM(365),TD2P(336),TWB(336),TEFF(336)
      DIMENSION PSAT(120),IN(5,20),DP(5,20),DX(5,20),ALPHA(5,20),CON(5,2
     10),ROW(5,20),CP(5,20),CW(20)
      DIMENSION INT(60),QS(2,20),BB(40),BMUL(40,20),TDI(30),TWI(30),TEI(
     130),TDIAV(30),TWIAV(30),TEIAV(30),TSOIL(20)
      DIMENSION XI(20),AZ(20),LAYMAX(20),QLATC(20),HI(20),HO(20),NMAX(20
     1),ITWALL(20),QSW(20),QW(20),AREA(20),TDD(14),TWD(14),TED(14),TDAVG
     2(14),TWAVG(14),TEAVG(14),IDATA(13),LST(2),TRANS(20),ASOIL(20),
     3AJIT(20)
      JJJJ=1
C
C INITIALIZE ALL MATRIX ELEMENTS TO ZERO.
C
 1311 DO 1 I=1,40
      DO 1 J=1,40
      DO 1 K=1,20
    1 AINV(I,J,K)=0.0
      DO 2 I=1,40
      T(I)=0.0
      DO 2 J=1,2
    2 INDEX(I,J)=0
      DO 3 I=1,40
      DO 3 J=1,20
      BMUL(I,J)=0.0
    3 TWALL(I,J)=0.0
      DO 5 I=1,365
    5 EQTIM(I)=0.0
      DO 6 I=1,336
    6 TD2P(I)=TWB(I)=TEFF(I)=0.0
      DO 7 I=1,120
    7 PSAT(I)=0.0
      DO 8 I=1,5
      DO 8 J=1,20
      IN(I,J)=0
    8 DP(I,J)=DX(I,J)=ALPHA(I,J)=CON(I,J)=ROW(I,J)=CP(I,J)=0.0
      DO 9 I=1,60
    9 INT(I--=0
      DO 10 I=1,2
      DO 10 J=1,20
   10 QS(I,J)=0.0
      DO 302 I=1,30
  302 TDI(I)=TWI(I)=TEI(I)=TDIAV(I)=TWIAV(I)=TEIAV(I)=0.0
      DO 303 I=1,20
      CW(I)=0.0
```

```
      LAYMAX(I)=NMAX(I)=ITWALL(I)=0
  303 XI(I)=AZ(I)=QLATC(I)=HI(I)=HO(I)=QSW(I)=QW(I)=AREA(I)=TRANS(I)=ASO
     1IL(I)=TSOIL(I)=AJIT(I)=0.0
      DO 304 I=1,14
  304 TDD(I)=TWD(I)=TED(I)=TDAVG(I)=TWAVG(I)=TEAVG(I)=0.0
      DO 305 I=1,13
  305 IDATA(I)=0
      DO 306 I=1,2
  306 LST(I)=0
C
C READ INPUT DATA AND SET CONSTANTS.
C
      IF(JJJJ-1)307,307,308
  307 DO 11 I=1,365
   11 READ 1007,EQTIM(I)
      DO 12  I=50,120
   12 READ 1001,PSAT(I)
  308 READ 1006,IDATA
      READ 1003,ALT,ALAT,ALONG,NW,GG,HH,W,P,F1,QLITE,QEQUIP,D,HRS,LST(1)
     1,NOINT
      DO 16 J=1,NW
      READ 1020,AREA(J),LAYMAX(J),NMAX(J),HI(J),HO(J),ASOIL(J)
      IF(ASOIL(J))1312,15,15
 1312 READ 1001,TRANS(J),XI(J)
      IF(XI(J)-90.0)14,15,999
   14 READ 1003,AZ(J)
   15 LEM=LAYMAX(J)
      DO 16 K=1,LEM
   16 READ 1009,DP(K,J),DX(K,J),CON(K,J),ROW(K,J),CP(K,J)
      READ 1013,CFMIN,TCOIL,WCOIL,BF,F2,TD2,R2,TWB(1),TEFF(1)
      DO 18 J=1,NW
      IF(ASOIL(J))18,18,1703
 1703 READ 1008,TSOIL(J)
   18 CONTINUE
      IF(IDATA(1))19,19,21
   19 READ 1008,TO
      DO 20 J=1,NW
      NEM=NMAX(J)&1
      DO 20 K=1,NEM
   20 TWALL(K,J)=TO
      GO TO 23
   21 DO 22 J=1,NW
      NEM=NMAX(J)&1
      DO 22 K=1,NEM
      READ 1008,TO
   22 TWALL(K,J)=TO
   23 READ 1001,DT
      IHRS=HRS
      NODAYS=IHRS/24
      IF(NOINT)1701,1701,1702
 1702 NOO=2*NOINT
      DO 17 I=1,NOO
   17 READ 1006,INT(I)
 1701 ID=D
      LMN=25
      KIND=0
      QLH=0.0
      ADT=0.0
      IHRNO=1
      NTAU=0
```

```
      PI=3.14159265
      OM=PI/12.0
      ON=180./PI
      DR=0.1
      R=1.0
      MOND=1
      GIL=TD2
      VS=GG*HH*W
      READ 1021,TA1,TA2,TD11,TD12,R11,R12
C
C CALCULATE INTENSITY OF SOLAR RADIATION FOR EACH EXPOSED BOUNDARY.
C
   25 LST(2)=LST(1)&1
      DO 53 I=1,2
      LSTM=LST(I)
  251 DO 53 J=1,NW
      IF(ASOIL(J))252,53,53
  252 IF(IDATA(10))26,26,27
   26 C2=294.
      C3=3.183
      GO TO 28
   27 C2=200.
      C3=2.228
   28 IF(XI(J)-90.) 29,29,999
   29 ETAR=0.410152*SINF((ID-80)*PI/182.5)
      S1=TANF(ETAR)
      S2=SINF(ETAR)
      S3=COSF(ETAR)
      PHIR=ALAT/ON
      S4=TANF(PHIR)
      S5=SINF(PHIR)
      S6=COSF(PHIR)
      AZR=AZ(J)/ON
      XIR=XI(J)/ON
      S7=COSF(XIR)
      S8=SINF(XIR)
      IF(PHIR-(PI*0.5)) 30,998,998
   30 IF(ETAR&PHIR-(PI*0.5)) 31,998,998
   31 IF(ETAR) 34,34,32
   32 IF(PHIR-(PI*0.5-ETAR)) 34,33,33
   33 THETAR=0.0
      GO TO 35
   34 THETAR=ACOSF(S4*S1)
   35 THETAS=2.*PI-THETAR
      IN=ALONG/15
      TI=LSTM&EQTIM(ID)-ALONG/15.0&IN
      THETA=OM*TI
      S9=COSF(THETA)
      IF(THETA-THETAR) 36,37,37
   36 DIR=0.0
      DIF=0.0
      GO TO 52
   37 IF(THETA-THETAS) 38,38,36
   38 BETAR=ASINF(S5*S2-S6*S9*S3)
      S10=COSF(BETAR)
      S11=SINF(BETAR)
      IF(BETAR) 36,39,39
   39 IF(BETAR-(PI*0.5)) 392,391,392
  391 GAMMAR=AAR
      GO TO 393
```

```
  392 GAMMAR=ACOSF(1./S10*(S6*S2&S5*S9*S3))
  393 IF(GAMMAR) 40,40,41
   40 GAMMAR=GAMMAR&PI
   41 DIRNORM=C2*(1.-EXP(-C3*BETAR))
      S13=S10*COSF(GAMMAR-AZR)
      ALPHAR=ACOSF(S13*S7&S11*S8)
      S12=COSF(ALPHAR)
      IF(ALPHAR-(PI*0.5)) 43,43,42
   42 DIR=0.0
      GO TO 49
   43 IF(S13) 45,44,44
   44 FALPHA=0.35*S13**2.&0.45*S13&0.55
      GO TO 48
   45 IF(S13&0.04) 47,47,46
   46 FALPHA=0.625*S13**2.&0.525*S13&0.55
      GO TO 48
   47 FALPHA=0.44
   48 DIR=DIRNORM*S12
   49 DIF1=S11*(FALPHA*(1.-S8)&S8)
      DIF2=0.677E-06*DIRNORM**2-1.5E-04*DIRNORM&0.0183
      DIF=DIF1/DIF2
   52 TOT=DIR&DIF
      QS(I,J)=TOT
   53 CONTINUE
      QST=0.0
      QSOLAR=0.0
      DO 54 J=1,NW
      QSW(J)=QS(2,J)
      QSOLAR=TRANS(J)*QSW(J)*AREA(J)&QSOLAR
   54 QST=QST&QS(2,J)*AREA(J)
C
C FOR EACH HOUR OF OCCUPANCY AFTER THE FIRST, RESET HOUR NUMBER AND SET
C CONDITIONS AT THE END OF THE PRECEDING HOUR TO THOSE AT THE BEGINNING
C OF THE SUCCEEDING HOUR. READ THE INLET CONDITIONS FOR THE SUCCEEDING HOUR.
C
      IF(IHRNO-1)57,24,57
   55 DO 56 J=1,NW
   56 QS(1,J)=QS(2,J)
      LSTM=LSTM&1
      IHRNO=IHRNO&1
      IF(24-LSTM)5612,5612,251
 5612 LSTM=0
      ID=ID&1
      IF(365-ID)5611,251,251
 5611 ID=1
      GO TO 251
   57 TD11=TD12
      R11=R12
      TA1=TA2
      ADT=DT
      IF(IDATA(12))181,181,182
  181 READ 1018,P,F1,CFMIN,QLITE,QEQUIP
  182 IF(IDATA(13))183,183,60
  183 READ 1019,TD12,TA2,R12
      GO TO 60
   58 QST=0.0
      QSOLAR=0.0
      DO 59 J=1,NW
      QSO=QS(1,J)&ADT*(QS(2,J)-QS(1,J))
      QSW(J)=QSO
```

```
      QSOLAR=TRANS(J)*QSW(J)*AREA(J)&QSOLAR
   59 QST=QST&QSO
C
C FOR TIME INCREMENTS DURING THE HOUR, DETERMINE INLET CONDITIONS AS A
C LINEAR INTERPOLATION BETWEEN HOURLY VALUES.
C
   60 TD1=TD11-ADT*(TD11-TD12)
      R1=R11-ADT*(R11-R12)
      PG=5.132*EXP(0.0329*TD1)
      PGPP=R1*PG
      BP=0.98E-06*ALT**2-0.0759*ALT&2116.2
      W1=(0.622*PGPP)/(BP-PGPP)
      TA=TA1-ADT*(TA1-TA2)
      LL=1
C
C CALCULATE NEW INLET CONDITIONS WITH AIR-CONDITIONING. DETERMINE PROPERTIES
C OF THE INLET AIR FOR THE BEGINNING OF THE TIME INCREMENT.
C
      IF(IDATA(7))403,403,402
  402 TD1=TD2&(F2/F1)*(TD1-TD2)
      PGPP=5.132*R2*EXP(0.0329*TD2)
      W2=(0.622*PGPP)/(BP-PGPP)
      W1=W2&(F2/F1)*(W1-W2)
      ADMIX=(F1-CFMIN)/F1&BF*(1.-((F1-CFMIN)/F1))
      TDA=TCOIL&ADMIX*(TD1-TCOIL)
      WA=WCOIL&ADMIX*(W1-WCOIL)
      E1=EXP(0.0329*TDA)
      PGPP=WA*BP/(WA&0.622)
      PG=5.132*E1
      R1=PGPP/PG
      WAC=60.0*CFMIN*DT*(0.018744*BP-0.0962*R1*E1)/(TDA&459.69)
      HF=1093.9-0.567*TCOIL
      PAIRCOND=0.24*WAC*(TD1-TDA)/DT&WAC*(W1-WA)*HF/DT
      TD1=TDA
      W1=WA
      GO TO 61
  403 PAIRCOND=0.0
   61 E1=EXP(0.0329*TD1)
      E2=EXP(0.0329*TD2)
      HAS1=0.24*TD2
      HVS1=1061.0&0.444*TD2
      HA1=0.24*TD1
      HV1=1061.0&0.444*TD1
      HFG=1093.9-0.567*TD2
      WAS1=VS*(0.018744*BP-0.0962*R2*E2)/(TD2&459.69)
      WVS1=VS*(0.05987*R2*E2)/(TD2&459.69)
      WA1=60.0*F1*DT*(0.018744*BP-0.0962*R1*E1)/(TD1&459.69)
      WV1=60.0*F1*DT*(0.05987*R1*E1)/(TD1&459.69)
      HS1=WAS1*HAS1&WVS1*HVS1
      H1=WA1*HA1&WV1*HV1
      WAO=WA1&WAS1
C
C CALCULATE THE HEAT TRANSFER THROUGH THE BOUNDARIES DUE TO TEMPERATURE
C DIFFERENCES AND DUE TO MOISTURE CONDENSATION.
C
      IF(IDATA(6))69,69,70
   69 QWC=0.0
      QLH=0.0
      NTAU=NTAU&1
      IHRN=IHRNO-1
```

```
      GO TO 146
   70 DO 71 J=1,NW
      ILL=0
      LEM=LAYMAX(J)
      DO 71 K=1,LEM
      IN(K,J)=DP(K,J)/DX(K,J)&1&ILL
   71 ILL=IN(K,J)
      JWALL=1
      LAY=1
      I=1
   72 NEM=NMAX(JWALL)&1
      DO 4 INA=1,NEM
      DO 4 JNA=1,NEM
      A(INA,JNA)=0.0
    4 BB(INA)=0.0
  721 ALPHA(LAY,JWALL)=CON(LAY,JWALL)/(ROW(LAY,JWALL)*CP(LAY,JWALL))
      BASIL=1.0&CON(LAY&1,JWALL)*DX(LAY,JWALL)/(DX(LAY&1,JWALL)*CON(LAY,
     1JWALL))&ROW(LAY,JWALL)*CP(LAY,JWALL)*DX(LAY,JWALL)**2/(2.0*CON(LAY
     2,JWALL)*DT)&ROW(LAY&1,JWALL)*CP(LAY&1,JWALL)*DX(LAY,JWALL)*DX(LAY&
     31,JWALL)/(2.0*CON(LAY,JWALL)*DT)
   73 IF(I-1)76,76,82
   76 ITD2=TD2
      PS=PSAT(ITD2)&(TD2-ITD2)*(PSAT(ITD2&1)-PSAT(ITD2))
      PO=PS*R2
      ITWALL(JWALL)=TWALL(1,JWALL)
      IELF1=ITWALL(JWALL)
      ELF2=TWALL(1,JWALL)
      PSW=PSAT(IELF1)&(ELF2-IELF1)*(PSAT(IELF1&1)-PSAT(IELF1))
      TENV=(TD2&TWALL(1,JWALL))/2.0
      ROAIR=3.25E-07*TENV**2.0-1.86E-04*TENV&0.0863
   77 C=2.8249*HFG*HI(JWALL)*(PO/(BP-PO)-PSW/(BP-PSW))/ROAIR
      CW(JWALL)=C*AREA(JWALL)*DT/HFG
      IF(CW(JWALL))772,79,771
  771 AJIT(JWALL)=AJIT(JWALL)&CW(JWALL)
      GO TO 79
  772 IF(ABSF(CW(JWALL))-AJIT(JWALL))771,771,774
  774 CW(JWALL)=-AJIT(JWALL)
      C=CW(JWALL)*HFG/(AREA(JWALL)*DT)
      GO TO 771
   79 QLATC(JWALL)=C
      IF(NTAU)80,80,81
   80 A(I,I)=1.0&CON(LAY,JWALL)/(HI(JWALL)*DX(LAY,JWALL))&ROW(LAY,JWALL)
     1*CP(LAY,JWALL)*DX(LAY,JWALL)/(2.0*HI(JWALL)*DT)
      A(I,I&1)=-CON(LAY,JWALL)/(HI(JWALL)*DX(LAY,JWALL))
   81 BB(I)=ROW(LAY,JWALL)*CP(LAY,JWALL)*DX(LAY,JWALL)/(2.0*HI(JWALL)*DT
     1)*TWALL(I,JWALL)&TD2&C/HI(JWALL)
      I=I&1
   82 IF(I-IN(LAY,JWALL))83,83,86
   83 IF(NTAU)84,84,85
   84 A(I,I-1)=-1.0
      A(I,I)=DX(LAY,JWALL)**2/(ALPHA(LAY,JWALL)*DT)&2.
      A(I,I&1)=-1.0
   85 BB(I)=DX(LAY,JWALL)**2*TWALL(I,JWALL)/(ALPHA(LAY,JWALL)*DT)
      I=I&1
      GO TO 82
   86 IF(LAY-LAYMAX(JWALL))87,90,996
   87 IF(NTAU)88,88,89
   88 A(I,I-1)=-1.0
      A(I,I)=BASIL
      A(I,I&1)=-CON(LAY&1,JWALL)*DX(LAY,JWALL)/(DX(LAY&1,JWALL)*CON(LAY,
     1JWALL))
   89 BB(I)=(ROW(LAY,JWALL)*CP(LAY,JWALL)*DX(LAY,JWALL)**2.&ROW(LAY&1,JW
```

```
     1ALL)*CP(LAY&1,JWALL)*DX(LAY,JWALL)*DX(LAY&1,JWALL))*TWALL(I,JWALL)
     2/(2.0*CON(LAY,JWALL)*DT)
      I=I&1
      LAY=LAY&1
      IF(LAY-LAYMAX(JWALL))721,721,90
   90 IF(ASOIL(JWALL))91,92,96
   91 TAJ=TA
      GO TO 93
   92 TAJ=0.5*(TD2&TA)
   93 IF(NTAU)94,94,95
   94 A(I,I-1)=-CON(LAY,JWALL)/(HO(JWALL)*DX(LAY,JWALL))
      A(I,I)=-A(I,I-1)&1.0&ROW(LAY,JWALL)*DX(LAY,JWALL)*CP(LAY,JWALL)/(2
     1.0*HO(JWALL)*DT)
   95 IF(ASOIL(JWALL))951,952,96
  951 BB(I)=(1.0-TRANS(JWALL))*QSW(JWALL)/HO(JWALL)&TAJ&ROW(LAY,JWALL)*C
     1P(LAY,JWALL)*DX(LAY,JWALL)/(2.0*DT*HO(JWALL))*TWALL(I,JWALL)
      GO TO 103
  952 BB(I)=TAJ&ROW(LAY,JWALL)*CP(LAY,JWALL)*DX(LAY,JWALL)/(2.0*DT*HO(JW
     1ALL))*TWALL(I,JWALL)
      GO TO 103
   96 IF(I-NMAX(JWALL)-1)100,100,996
  100 TWALL(I,JWALL)=TSOIL(JWALL)
      HARRY=ROW(LAY,JWALL)*CP(LAY,JWALL)*DX(LAY,JWALL)**2/(CON(LAY,JWALL
     1)*DT)
      IF(NTAU)101,101,102
  101 A(I,I-1)=1.0
      A(I,I)=2.0&HARRY
  102 BB(I)=HARRY*TWALL(I,JWALL)&TSOIL(JWALL)
  103 IF(NTAU)104,104,1351
  104 NEM=NMAX(JWALL)&1
      DO 108 I=1,NEM
  108 INDEX(I,1)=0
      II=0
  109 AMAX=-1.
      DO 110 I=1,NEM
      IF(INDEX(I,1))110,111,110
  111 DO 112 J=1,NEM
      IF(INDEX(J,1))112,113,112
  113 TEMP=ABSF(A(I,J))
      IF(TEMP-AMAX)112,112,114
  114 IROW=I
      ICOL = J
      AMAX=TEMP
  112 CONTINUE
  110 CONTINUE
      IF(AMAX)225,115,116
  115 PRINT 133
  133 FORMAT(11H ZERO PIVOT)
      GO TO 69
  116 INDEX(ICOL,1)=IROW
      IF(IROW-ICOL)119,118,119
  119 DO 120 J=1,NEM
      TEMP=A(IROW,J)
      A(IROW,J)=A(ICOL,J)
  120 A(ICOL,J)=TEMP
      II=II&1
      INDEX(II,2)=ICOL
  118 PIVOT=A(ICOL,ICOL)
      A(ICOL,ICOL)=1.0
      PIVOT=1./PIVOT
```

```
      DO 121 J=1,NEM
  121 A(ICOL,J)=A(ICOL,J)*PIVOT
      DO 122 I=1,NEM
      IF(I-ICOL)123,122,123
  123 TEMP=A(I,ICOL)
      A(I,ICOL)=0.0
      DO 124 J=1,NEM
  124 A(I,J)=A(I,J)-A(ICOL,J)*TEMP
  122 CONTINUE
      GO TO 109
  125 ICOL=INDEX(II,2)
      IROW=INDEX(ICOL,1)
      DO 126 I=1,NEM
      TEMP=A(I,IROW)
      A(I,IROW)=A(I,ICOL)
  126 A(I,ICOL)=TEMP
      II=II-1
  225 IF(II)125,127,125
  127 DO 135 I=1,NEM
      BMUL(I,JWALL)=BB(I)
      DO 135 J=1,NEM
  135 AINV(I,J,JWALL)=A(I,J)
 1351 IF(JWALL-NW)143,142,995
  143 JWALL=JWALL&1
      I=1
      LAY=1
      GO TO 72
  142 DO 144 K=1,NW
  144 QW(K)=HI(K)*AREA(K)*(TD2-TWALL(1,K))
      QWC=0.0
      QLH=0.0
      DO 145 J=1,NW
      QWC=QWC&QW(J)
  145 QLH=QLH&QLATC(J)*AREA(J)
C
C CALCULATE METABOLIC HEAT ENERGIES.
C
      NTAU=NTAU&1
      IHRN=IHRNO-1
  146 IF(TEFF(IHRNO)-87.0)149,149,147
  147 IF(TEFF(IHRNO)-102.0)148,148,994
  148 QT=-1.508*TEFF(IHRNO)**2&259.7*TEFF(IHRNO)-10795.2
      GO TO 151
  149 IF(TEFF(IHRNO)-50.0)993,150,150
  150 QT=-1.482*TEFF(IHRNO)&514.0
  151 IF(TD2-50.0)992,152,152
  152 QSENS=-0.06875*TD2**2&1.625*TD2&523.0
      QSEN=QSENS*P
      QLA=QT-QSENS
      QL=QLA*P
C
C CALCULATE THE SHELTER DRY-BULB TEMPERATURE AND RELATIVE HUMIDITY
C AT THE END OF THE TIME INCREMENT.
C
  153 IF(R-1.0)154,155,155
  154 QL=QL*R
      PRINT 2001,IHRN,R
  155 DQ=HS1&H1&(QSEN&QL*(HVS1/HFG)-QWC&QLITE&QEQUIP-PAIRCOND&QSOLAR-QLH
     1)*DT
      WVL=QL*DT/HFG
```

```
      WVCOND=QLH*DT/HFG
      WVO=WV1&WVL&WVS1-WVCOND
      IF(WVCOND)1554,1554,1556
 1556 IF(WVO)1553,1554,1554
 1553 WVO=0.0
 1554 TD2P(IHRNO)=(DQ-1061.0*WVO)/(0.444*WVO&0.24*WAO)
      IF(ABSF(GIL-TD2P(IHRNO))-1.00)1552,1551,1551
 1552 LL=IDATA(3)
      GO TO 163
 1551 IF(TD2P(IHRNO)-50.0)986,156,156
  156 IF(WVO)1561,1561,1563
 1561 PV2=0.0
      R2P=0.0
      GO TO 1562
 1563 PV2=BP/(0.622*WAO/WVO&1.0)
      EPS=EXPF(0.0329*TD2P(IHRNO))
      R2P=PV2/(5.132*EPS)
 1562 IF(R-0.0)157,157,158
  157 R2P=1.0
      GO TO 163
  158 IF(MOND-2)159,160,160
  159 MOND=2
      IF(R2P-1.0)163,163,160
  160 IF(R2P-1.0)162,162,161
  161 R=R-DR
      GO TO 153
  162 R=R&DR
      DR=0.1*DR
      MOND=MOND&1
      IF(MOND-4)161,161,163
  163 IF(LL-IDATA(3))164,165,991
  164 TD2=0.5*(TD2&TD2P(IHRNO))
      GIL=TD2
      R2=0.5*(R2&R2P)
C
C CALCULATE THE SHELTER WET-BULB AND EFFECTIVE TEMPERATURES.
C
      DO 1641 I=1,NW
 1641 AJIT(I)=AJIT(I)-CW(I)
      LL=LL&1
      GO TO 61
  165 DO 1555 K=1,NW
      NEM=NMAX(K)&1
      DO 1555 I=1,NEM
      T(I)=0.0
      DO 1555 J=1,NEM
      A(I,J)=AINV(I,J,K)
      BB(J)=BMUL(J,K)
      T(I)=T(I)&A(I,J)*BB(J)
 1555 TWALL(I,K)=T(I)
      IF(R2P-1.0)167,166,990
  166 TWB(IHRNO)=TD2P(IHRNO)
      TEFF(IHRNO)=TD2P(IHRNO)
      GO TO 168
  167 TWO=TD2P(IHRNO)
      DWO=10.0
      MM=1
  168 PSS=5.132*EXPF(0.0329*TWO)
      TWB(IHRNO)=(( BP  -PSS)*TD2P(IHRNO)-2800.0*(PSS-PV2))/( BP  &1.3*P
     1V2-2.3*PSS)
```

```
  169 IF(TWB(IHRNO)-TWO)170,172,171
  170 TWO=TWO-DWO
      GO TO 168
  171 TWO=TWO&DWO
      DWO=0.1*DWO
      MM=MM&1
      IF(MM-3)170,170,172
  172 TEF1=107.5*(TD2P(IHRNO)-TWB(IHRNO))&62.3*TWB(IHRNO)
      TEFF(IHRNO)=TEF1/(62.3&TD2P(IHRNO)-TWB(IHRNO))
C
C PRINT RESULTS FOR THE HOUR.
C
      IF(KIND-IDATA(5))173,174,989
  173 KIND=KIND&1
      GO TO 180
  174 IF(IDATA(11))178,178,175
  175 IF(IHRNO-1)988,176,177
  176 PRINT 2002
      PRINT 2037
      PRINT 2003
      PRINT 2004
      PRINT 2005
      PRINT 2030
      PRINT 2031
  177 IF(IHRNO-LMN)1772,1771,1772
 1771 LMN=LMN&24
      PRINT 2038
 1772 F3=F1/P
      PRINT 2006,IHRNO,F3,TD2P(IHRNO),TWB(IHRNO),TEFF(IHRNO),PAIRCOND,QW
     1C,QLH,QSOLAR,QSEN,QL,QEITE,QEQUIP
  178 IF(IHRNO-IHRS)179,187,987
  179 KIND=1
  180 TD2=TD2P(IHRNO)
      R2=R2P
      ADT=ADT&DT
      TEFF(IHRNO&1)=TEFF(IHRNO)
   24 IF(ADT-1.00001)58,55,55
C
C ERROR MESSAGES
C
  999 PRINT 2007,J,XI(J)
      GO TO 5000
  998 PRINT 2008
      GO TO 5000
  997 PRINT 2009
      GO TO 5000
  996 PRINT 2010
      GO TO 5000
  995 PRINT 2011
      GO TO 5000
  994 PRINT 2012,IHRN,TEFF(IHRNO)
      GO TO 148
  993 PRINT 2012,IHRN,TEFF(IHRNO)
      GO TO 150
  992 PRINT 2014,IHRN,TD2P(IHRNO)
      GO TO 152
  991 PRINT 2015
      GO TO 165
  990 PRINT 2016
      GO TO 166
```

```
  989 PRINT 2017
      GO TO 174
  988 PRINT 2018
      GO TO 176
  987 PRINT 2019
      GO TO 187
  986 PRINT 2036,TD2P(IHRNO),IHRN
      GO TO 156
C
C CALCULATE AND PRINT TIME-AVERAGE SHELTER TEMPERATURES.
C
  187 TDMAX=TD2P(1)
      IHH=IHRS-1
      LM=1
  188 DO 190 L1=1,IHH
      IF(TDMAX-TD2P(L1&1))189,190,190
  189 TDMAX=TD2P(L1&1)
      LM=L1&1
  190 CONTINUE
      PRINT 2020,TDMAX,LM
      TDMIN=TD2P(1)
      LM=1
  191 DO 193 L1=1,IHH
      IF(TDMIN-TD2P(L1&1))193,193,192
  192 TDMIN=TD2P(L1&1)
      LM=L1&1
  193 CONTINUE
      PRINT 2032,TDMIN,LM
      TWMAX=TWB(1)
      LM=1
  194 DO 196 L1=1,IHH
      IF(TWMAX-TWB(L1&1))195,196,196
  195 TWMAX=TWB(L1&1)
      LM=L1&1
  196 CONTINUE
      PRINT 2021,TWMAX,LM
      TWMIN=TWB(1)
      LM=1
  197 DO 199 L1=1,IHH
      IF(TWMIN-TWB(L1&1))199,199,198
  198 TWMIN=TWB(L1&1)
      LM=L1&1
  199 CONTINUE
      PRINT 2033,TWMIN,LM
      ETMAX=TEFF(1)
      LM=1
  200 DO 202 L1=1,IHH
      IF(ETMAX-TEFF(L1&1))201,202,202
  201 ETMAX=TEFF(L1&1)
      LM=L1&1
  202 CONTINUE
      PRINT 2022,ETMAX,LM
      ETMIN=TEFF(1)
      LM=1
  203 DO 205 L1=1,IHH
      IF(ETMIN-TEFF(L1&1))205,205,204
  204 ETMIN=TEFF(L1&1)
      LM=L1&1
  205 CONTINUE
      PRINT 2034,ETMIN,LM
```

```
      PRINT 2023
      PRINT 2024
      TDW=0.0
      TWW=0.0
      TEW=0.0
      DO 213 J=1,IHRS
      TDW=TDW&TD2P(J)
      TWW=TWW&TWB(J)
  213 TEW=TEW&TEFF(J)
      TDS=TDW/HRS
      TWS=TWW/HRS
      TES=TEW/HRS
      PRINT 2035,TDS,TWS,TES
      IF(NODAYS)5000,209,206
  206 LB=1
      LE=24
      DO 2071 IDAY=1,NODAYS
      DO 207 J=LB,LE
      TDD(IDAY)=TDD(IDAY)&TD2P(J)
      TWD(IDAY)=TWD(IDAY)&TWB(J)
  207 TED(IDAY)=TED(IDAY)&TEFF(J)
      LB=LB&24
 2071 LE=LE&24
      PRINT 2025
      DO 208 IDAY=1,NODAYS
      TDAVG(IDAY)=TDD(IDAY)/24.0
      TWAVG(IDAY)=TWD(IDAY)/24.0
      TEAVG(IDAY)=TED(IDAY)/24.0
  208 PRINT 2026,IDAY,TDAVG(IDAY),TWAVG(IDAY),TEAVG(IDAY)
  209 IF(NOINT)5000,5000,210
  210 PRINT 2027
      ND=2*NOINT-1
      DO 212 NI=1,ND,2
      MM=(NI&1)/2
      ILT=INT(NI)
      ILLL=INT(NI&1)
      DO 211 MI=ILT,ILLL
      TDI(MM)=TDI(MM)&TD2P(MI)
      TWI(MM)=TWI(MM)&TWB(MI)
  211 TEI(MM)=TEI(MM)&TEFF(MI)
      TDIAV(MM)=TDI(MM)/(INT(NI&1)-INT(NI)&1)
      TWIAV(MM)=TWI(MM)/(INT(NI&1)-INT(NI)&1)
      TEIAV(MM)=TEI(MM)/(INT(NI&1)-INT(NI)&1)
  212 PRINT 2028,INT(NI),INT(NI&1),TDIAV(MM),TWIAV(MM),TEIAV(MM)
      IF(JJJJ-IDATA(4))186,5000,5000
  186 JJJJ=JJJJ&1
      GO TO 1311
C
C
 1001 FORMAT(F7.3,F7.1)
 1003 FORMAT(F7.1,F4.1,F5.1,I2,3F7.1,F5.0,F9.2,2F8.1,2F3.0,2I2)
 1006 FORMAT(13I3)
 1007 FORMAT(F5.2)
 1008 FORMAT(F4.1)
 1009 FORMAT(2F6.3,2F6.2,F6.3)
 1013 FORMAT(F9.2,F4.1,F8.5,F4.2,F9.2,F4.1,F4.2,2F4.1)
 1018 FORMAT(F5.0,2F9.2,2F8.1)
 1019 FORMAT(2F4.1,F5.2)
 1020 FORMAT(F7.1,2I3,2F5.2,F3.0)
 1021 FORMAT(4F4.1,2F5.2)
```

```
2001 FORMAT(1H ,*R DURING HOUR*,I3,* IS *,F7.4,* WHICH IS LESS THAN 1.0
    1. THEREFORE, THE LATENT ENERGY INTRODUCED BY THE OCCUPANTS HAS BEE
    2N REDUCED.*)
2002 FORMAT(1H1,25X,*NOMINAL OCCUPANT ACTIVITY LEVEL*,7X,*400  BTU/HR
    1-OCCUPANT*)
2003 FORMAT(1H0,68X,*LOADS    (BTU/HR)*)
2004 FORMAT(1H0,7X,*VENT*,59X,*TRANS.  METABOLIC   METABOLIC*)
2005 FORMAT(1H ,*TIME   RATE    DBT    WBT    ET     AIRCOND   BOUNDARY
    1     CONDEN.     SOLAR   SENSIBLE     LATENT   LIGHTING  EQUIPMENT
    2*)
2006 FORMAT(1H ,I4,3X,4(F4.1,3X),8(F8.0,3X))
2007 FORMAT(1H ,*INCLINATION ANGLE XI(*,I2,*) IS *,F6.2,*. THIS VALUE M
    1UST BE 90 DEG. OR LESS.*)
2008 FORMAT(1H ,*THE LATITUDE OF THE SHELTER IS GREATER THAN THE PROGRA
    1M CAN HANDLE FOR THIS DAY OF THE YEAR.*)
2010 FORMAT(1H ,*THE LIMIT ON LAYMAX OR ON NMAX OF BOUNDARY *,I2,* HAS
    1BEEN EXCEEDED.*)
2011 FORMAT(1H ,*THE NUMBER OF SHELTER BOUNDARIES, NW, HAS BEEN EXCEEDE
    1D,   MACHINE ERROR.*)
2012 FORMAT(1H ,*SHELTER EFFECTIVE TEMPERATURE DURING HOUR*,I4,* IS *F5
    1.1,* WHICH EXCEEDS THE LIMITS OF THE METABOLIC RELATIONS.*)
2014 FORMAT(1H ,*DRY-BULB TEMPERATURE DURING HOUR *,I3,* IS *,F5.1,* WH
    1ICH EXCEEDS THE LIMITS OF THE METABOLIC RELATIONS.*)
2015 FORMAT(1H ,* THE NUMBER OF ITERATIONS FOR AN INCREMENT HAS EXCEEDE
    1D THE VALUE OF IDATA(3).*)
2016 FORMAT(1H ,*THE RELATIVE HUMIDITY IN THE SHELTER HAS EXCEEDED SATU
    1RATION.*)
2017 FORMAT(1H ,*THE NUMBER OF INCREMENTS IN THE HOUR EXCEEDS THE VALUE
    1 OF IDATA(5)*)
2018 FORMAT(1H ,*THE HOUR NUMBERS ARE NOT INDEXING PROPERLY.*)
2019 FORMAT(1H ,*THE HOUR NUMBER HAS EXCEEDED THE LENGTH OF OCCUPANCY.*
    1)
2020 FORMAT(1H0,15X,*MAX. DRY-BULB TEMP. DURING OCCUPANCY*,6X,F4.1,* AT
    1*,I4,* HOURS AFTER BEGINNING OF OCCUPANCY*)
2021 FORMAT(1H0,15X,*MAX. WET-BULB TEMP. DURING OCCUPANCY*,6X,F4.1,* AT
    1*,I4,* HOURS AFTER BEGINNING OF OCCUPANCY*)
2022 FORMAT(1H0,15X,*MAX EFFECTIVE TEMP. DURING OCCUPANCY*,6X,F4.1,* AT
    1*,I4,* HOURS AFTER BEGINNING OF OCCUPANCY*)
2023 FORMAT(1H1,39X,*TIME-AVERAGE TEMPERATURE VALUES*)
2024 FORMAT(1H0,26X,*FOR ENTIRE DURATION OF OCCUPANCY*,16X,*DBT*,7X,*WB
    1T*,8X,*ET*)
2025 FORMAT(1H0,26X,*FOR EACH DAY OF OCCUPANCY*)
2026 FORMAT(1H ,64X,*DAY *,I2,3X,F5.1,2(5X,F5.1))
2027 FORMAT(1H0,26X,*FOR SPECIFIC INTERVALS*,16X,*HRS*)
2028 FORMAT(1H ,59X,I4,*-*,I4,5X,F5.1,2(5X,F5.1))
2030 FORMAT(1H ,* HR    CFM/    DEG    DEG    DEG*)
2031 FORMAT(1H ,8X,*OCC      F      F      F*)
2032 FORMAT(1H0,15X,*MIN. DRY-BULB TEMP. DURING OCCUPANCY*,6X,F4.1,* AT
    1*,I4,* HOURS AFTER BEGINNING OF OCCUPANCY*)
2033 FORMAT(1H0,15X,*MIN. WET-BULB TEMP. DURING OCCUPANCY*,6X,F4.1,* AT
    1*,I4,* HOURS AFTER BEGINNING OF OCCUPANCY*)
2034 FORMAT(1H0,15X,*MIN EFFECTIVE TEMP. DURING OCCUPANCY*,6X,F4.1,* AT
    1*,I4,* HOURS AFTER BEGINNING OF OCCUPANCY*)
2035 FORMAT(1H ,73X,F5.1,2(5X,F5.1))
2036 FORMAT(1H ,*TD2P=*,F10.1,* AT *,I3)
2037 FORMAT(1H0,36X,*VALUES ARE FOR LAST TIME INCREMENT OF EACH HOUR*)
2038 FORMAT(1X)
5000 STOP
     END
```

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