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DESCRIPTION OF AN EARTH CONTACT MODELING CAPABILITY IN THE DOE-2.1B ENERGY ANALYSIS PROGRAM

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ABSTRACT

The problem of determining the heat transfer processes in residences and commercial structures requires accurate analytical models if one is to adequately define energy conservation measures. Various energy analysis computer simulation programs are presently available for use in the public sector. Among these programs, DOE-2.1B represents the state of the art in determining building thermal loads and energy usage quantities. However, the current version of DOE-2.1B does not rigorously deal with the problem of heat transfer in earth contact structures. This situation, although minor when compared with the relatively comprehensive methodology utilized for the overall energy analysis of traditional above-grade buildings, nevertheless detracts from the primary goal of a well-defined simulation.

Recently, a research version of DOE-2.1B has been created with the addition of an algorithm that is used to analyze earth contact systems such as basements, crawl spaces, slabs, and berms. This paper describes the methodology used in the DOE-2.1B program revisions and gives numerous examples regarding its applications. The mathematical technique employs the generation of a two-dimensional finite-element model from simplified user input definitions from which weekly response factors are generated for those surfaces in contact with the ground. Weekly averaged weather parameters provide the external excitations used to define the thermal load within the earth contact space.

INTRODUCTION

During the past decade, there has been increasing interest both in government agencies and among private sector firms in the understanding and the accurate determination of the energy usage in buildings. One aspect of this interest has focused on the development of various computer programs which simulate and/or predict the heating and cooling energy requirements. Such programs vary in their degree of sophistication, not only in their algorithmic formulation, but also in terms of the input/output requirements. The program designated DOE-2.1B (Lawrence Berkeley Laboratory, et.al. 1980) represents the state of the art in building energy analysis simulation programs which consider all three of the above factors of equal importance. A multitude of other computer programs exists which use either simplified heat transfer algorithms, the input and output of which are user-friendly or those that use more rigorous mathematical procedures such as finite element or difference techniques in which case the inputs/outputs are not usually

user oriented. DOE-2.1B represents a satisfactory mean between these two extremes.

The structure of DOE-2.1B can be described by considering the three primary tasks of the program: input, simulation, output. Input is treated by a Building Design Language (BDL) which is a program to analyze the input instructions, perform data assignments and data retrieval and control the operation of the remaining routines. The simulation portion is separated into four distinct, but inter-related sections (Lawrence Berkeley Laboratory, et.al. 1980):

(1) a LOADS analysis program, which calculates peak or design loads and hourly space loads imposed by ambient weather conditions and internal heat gains as well as variations in the size, location, orientation, construction and materials of walls, roofs, floors, etc.

(2) a SYSTEMS program capable of simulating the operation of secondary heating, ventilation and air-conditioning components including fans, coils, economizers and humidifiers.

(3) a PLANT program which models the operation of primary HVAC components such as boilers and chillers; electrical generation equipment such as diesel engines and turbines; and energy storage and solar heating/cooling systems.

(4) an ECONOMICS analysis program which calculates life cycle costs.

Outputs are generated upon completion of each of the above operations and the reports vary from typical peak load presentations to atypical annual scatter diagrams of space air temperature for each hour of the day.

The heat transfer algorithmic formulation used in DOE-2.1B is based on the use of room thermal response factors or weighting factors, introduced by Mitalas and Stephenson (1967). Weighting factors represent the time-series thermal response of a space due to a unit excitation in radiative, conductive or convective heat gain and space air temperature. Superposition is then used to define the response to any arbitrary external or internal excitation. In DOE-2.1B, weighting factors are generated from a one-time thermal balance matrix solution of the heat transfer equations. The response factor concept is also used to define the conductive heat transfer through each surface in the space. The factors represent the solution to the one-dimensional diffusion equation sampled at discrete time intervals of one hour for a surface such as shown in Figure 1.

One area in which DOE-2.1B is lacking is in its treatment of ground contact surfaces. Until recently, there has not been much interest in the use of underground or earth-tempered buildings as an energy conservation device. Because of this fact, the only tools which exist that predict the thermal performance of ground contact surfaces are either manual methods which provide very rough estimates or the aforementioned detailed and rigorous finite element or difference schemes used for

research purposes. DOE-2.1B uses a procedure recommended in ASHRAE Fundamentals (1981) in which either an effective U-value or reduced surface area is input by the user in conjunction with monthly values of ground temperatures to define the underground surface heat transfer. Now, however, an additional front-end (structured similar to the thermal balance generating weighting factor routines mentioned previously) has been added to the DOE-2.1B program. The method uses a one-time finite element solution to generate two-dimensional weekly response factors that can be used to accurately and economically predict earth contact heat losses and gains. The remainder of this paper will discuss the methodology used and implementation scheme employed in the DOE-2.1B revisions.

RESPONSE FACTOR METHODOLOGY REVIEW

Wall response factors represent the solution of the one-dimensional Fourier equation for a wall of thickness (L) as shown on Figure 1:

$$k(\partial^2 T/\partial x^2) = c(\partial T/\partial t) \tag{1}$$

where (c) is the volumetric heat capacity which is the product of density and specific heat; (k) is the conductivity and (T), the temperature. The response factors are used to define the surface conductive flux on each surface which can be written as:

$$\begin{aligned} q_o(t) &= [\sum_{j=0}^{\infty} X_o(j)T_{so}(t-j) - \sum_{j=0}^{\infty} Y_o(j)T_{sr}(t-j)]\, A_o \\ q_r(t) &= [\sum_{j=0}^{\infty} Y_r(j)T_{so}(t-j) - \sum_{j=0}^{\infty} Z_r(j)T_{sr}(t-j)]\, A_r \end{aligned} \tag{2}$$

where X, Y, and Z are the heat flux responses to a triangular excitation in wall surface temperatures, T_{so} and T_{sr}. X is the response on surface (o) from a pulse on (o); Z is the response on surface (r) from a pulse on (r); and Y represents the response on (o) from a pulse on (r) or the response on (r) from a pulse on (o). Space thermal load calculations are accomplished by performing a heat balance at each surface equating the conductive expressions above to the convective and radiative heat gains/losses. A finite number of terms is normally used in the above summations along with past values of heat flux quantities. This results from the fact that the responses are decaying exponentials so that after a certain time, all values are linearly related to the past value through a constant "common" ratio. While this procedure is a valid mathematical model for analyzing heat flow through finite walls, it does not suffice for the accurate analysis of ground contact or underground structures which are best treated in two or three dimensions. Considering Figure 2, however, it is easily seen that the one-dimensional response factor concept would be a valid approach to a solution if the factors were solved for using a two-dimensional technique. For example, conduction expressions for the surfaces in Figure 2 can be written as:

$$q_g(\tau) = [\sum_{j=0}^{\infty} X_{gg}(j)T_g(\tau-j) - \sum_{i=1}^{N}\sum_{j=0}^{\infty} Y_{ig}(j)T_i(\tau-j) - U_{dg}T_d]\ A_g$$

$$q_i(\tau) = [\sum_{j=0}^{\infty} Y_{gi}(j)T_g(\tau-j) + \sum_{i=1}^{\infty}\sum_{j=0}^{\infty} Y_{ki}(j)T_k(\tau-j) + U_{di}T_d - \sum_{j=0}^{\infty} X_{ii}(j)T_i(\tau-j)]\ A_i \qquad (3)$$

where the second subscript on each response factor designates the surface on which the response is obtained due to a unit excitation on the surface defined by the first subscript. The quantity N represents the total number of room surfaces, i, in contact with the ground and T_i the respective room surface temperatures. The deep ground temperature, T_d, has been assumed constant which results in a strictly steady state heat flow, thus the U-value is used. The time variable, τ , represents a weekly increment.

A simplification to equations 3 results if the response factors are generated from the exterior surface to the room air and vice versa. With T_{ref} representing the loads calculation temperature, the following equations are obtained:

$$q_g(\tau) = \{\sum_{j=0}^{\infty} X_{gg}(j)[T_g(\tau-j) - T_{ref}] - U_{dg}[T_d - T_{ref}]\}\ A_g$$

$$q_i(\tau) = \{\sum_{j=0}^{\infty} Y_{gi}(j)[T_g(\tau-j) - T_{ref}] + U_{di}[T_d - T_{ref}]\}\ A_i \qquad (4)$$

Equating the exterior ground surface conductive flux to the convective heat exchange with the outside air, $h_oA\ \Delta T$, the absorbed solar radiation, $\alpha I(\tau)$, and the radiation exchange with the surroundings, $qs(\tau)$, the ground surface temperature can be solved for explicitly.

$$T_g(\tau) = \{h_oA_gT_o(\tau) + X_{gg}(0)A_gT_{ref} - \sum_{j=1}^{\infty} X_{gg}(j)[T_g(\tau-j)-T_{ref}]$$

$$+ U_{dg}[T_d-T_{ref}]A_g + \alpha I(\tau) - qs(\tau)\}/[X_{gg}(0) + h_o]\ A_g \qquad (5)$$

which can be substituted into the room surface equation in (4) to obtain the heat gain by conduction through the surface i into the room. At this point, the conduction weighting factors are applied to obtain the zone load contribution for each surface.

The above equations define the procedure used in the LOADS or constant room temperature part of the DOE-2.1B program. Space air temperature variations are calculated by an expression which relates the change in air temperature to the change in the previously calculated load. For a space in contact with the ground, the sensible hourly load must be revised to reflect the newly calculated space temperature's effect. When T_{ref} changes to $T_r(\tau)$, the resulting change in conduction heat gain (equation 4) would be:

$$\Delta q(\tau) = \sum_{i=1}^{N} \Delta q_i(\tau) = \sum_{i=1}^{N} \{ \sum_{j=0}^{\infty} Y_{gi}(j)[T_{ref} - T_r(\tau-j)$$

$$+ \sum_{j=0}^{\infty} Y_{di}(j)[T_{ref} - T_r(\tau-j)]\} A_i \qquad (6)$$

$T_r(\tau)$ is the average weekly temperature and $q(\tau)$ the sum of the hourly fluxes over the week. Coupling of the hourly calculations to the weekly occurs by defining the current week's temperature to be the average of the previous week's hourly values. This average temperature is substituted into equation 6 and the resulting flux quantity defined. The change in thermal load is found by application of the appropriate space conduction weighting factors.

FINITE ELEMENT IMPLEMENTATION

The equations discussed above for the most part correspond to techniques already employed in the DOE-2.1B program and thus fit conveniently into the overall algorithmic structure. In addition to these revisions, of course, were those required to enable generation of the two-dimensional response factors. This formulation was accomplished with the development of a finite element model to represent the ground and ground contact surface layers and their respective thermal properties and boundary conditions. The method of finite elements is a numerical technique which involves the spatial sub-division into n-nodal points of the heat conduction region so that a system of simultaneous first-order ordinary differential equations are obtained with each equation corresponding to a particular nodal point. Once the model is defined, solution of the governing equations yield the temperatures and heat flux quantities of interest. Ceylon's (1979) exact solution methodology was used in the DOE-2.1B revisions. This procedure avoids the lengthy and time consuming techniques of the Euler or Crank-Nicolson methods normally used.

The series of ordinary differentail equations resulting from the spatial discretization by finite elements of the two-dimensional Fourier equation can be represented in matrix form as:

$$[C][T] + [K][T] = [P][S] \qquad (7)$$

where [C] is the capacitance matrix whose values are the thermal capacitance per unit width associated each node of the model; [K] is the conductance matrix representing the thermal conductance per unit width between nodes and the convective transfer coefficient per unit width for those nodes corresponding to the external boundaries; [P] is the driving function matrix which contains the convective transfer coefficients per unit width between a given driving function and a given node; [T] is the time varying temperature vector and [S] the vector driving functions, which in the DOE-2.1B revisions correspond to the ground surface temperature, deep ground temperature, and space air temperature.

Ceylon's exact analytical solution of equation 7 initially solves the homogeneous equation ([C][T]+[K][T]=0) to define a relationship among the [C] and [K] matrices and the resulting eigenvectors (characteristic vectors) and eigenvalues (characteristic values) of the complementary solution, i.e.:

$$[S][E] = [C][E][V] \tag{8}$$

where [E] is an (nxn) matrix containing the eigenvectors and [V] is a diagonal eigenvalue matrix. After certain matrix manipulations and definition of the particular solution to equation 7 through the use of integrating factors, the following response factors or coefficients in matrix form are obtained:

$$[B(0)] = [U][E][V]^{-1}[E]^{T}[P] - [U][E][V]^{-1}(([I]-e^{-[V]\tau})/_{\tau})[V]^{-1}[E][P]$$

$$(9)$$

$$[B(j)] = [U][E](e^{-[V]\tau})^{i-1}[V]^{-1}(([I]-e^{-[V]\tau})/_{\tau})^{2}[V]^{-1}[E][P]$$

where [U] is an (mxn) matrix which defines the relationship between the (m) desired outputs (heat fluxes at m boundaries) and the number of model nodes and (τ) is the time step which in the DOE-2.1B revisions is 1 week.

Construction of the finite element model and matrices is accomplished as indicated in the following steps:

(1) Determination of the azimuth and the vertical plane which defines the building section under analysis.

(2) Determination of the coordinates of intersection of walls in the model with the model plane.

(3) Adjustment of these coordinates so that the walls meet.

(4) Generation of the list of variables (driving temperatures and resultant heat fluxes).

(5) Generation of the list of vertical and horizontal values at which there are wall edges or ground layer boundaries.

(6) Generation of a list of contiguous block of constant thermal properties (wall and ground layers, except that a ground layer may constitute more than one such block if it is interrupted by a wall).

(7) Increasing the list of vertical and horizontal boundaries, within the constraint of not exceeding a fixed limit on eventual number of nodes.

(8) Generating the elements by dividing the blocks along vertical and horizontal boundaries. This also produces a list of nodes and

their coordinates, an index of the nodes of the corners of each element, and a pointer to the thermal properties of each element.

(9) Adjusting the coordinates of the nodes for the tilt of the ground. Nodes on walls and nodes inwward or downward from any wall are not adjusted. The adjustment also leaves the deep ground surface level.

(10) Calculation of the matrix elements using the geometrical and thermal property information. Internode conductances are calculated using a routine from Wang's (1979) program which assumes an additional node at the center of each element, divides the element into triangles, sums the internode conductances from these triangles and re-apportions the conductance through the central node as direct conductances among the bounding nodes. The capacitance is apportioned by dividing the element by lines from the centroid to the centers of the sides. The area corresponding to each node are equal to the sums of triangles.

DOE-2.1B INPUT DISCUSSION

Steps performed in construction of the two-dimensional finite element model consists of the transformation of the data obtained from the DOE-2.1B input to the matrices above which define the problem. The input to DOE-2.1B is constructed through the use of several new input language commands and keywords. Underground surfaces are described in a manner similar to the method currently used for exterior surfaces by defining their layer-by-layer structure as well as their geometric location and size. Similar requirements also exist for the new commands called GROUND-STRUCTURE and GROUND-WALL-MODEL which define the ground structure and geometric characteristics as follows:

The GROUND-STRUCTURE command, through the use of the following keywords, describes properties of the ground used for both the finite element modeling and subsequent loads calculations: (LAYERS) designates the layer structure of the ground; (DEEP-GROUND-TEMP) defines the deep ground temperature; (BARE-ALBEDO) and (SNOW-ALBEDO) define the fraction of incident solar radiation reflected from the ground surface during both clear and snow conditions; (BARE-ROUGHNESS) and (SNOW-ROUGHNESS) give the ratio of the characteristic roughness length to the height at which the wind speed is measured for both clear and snow conditions which is used to calculate the surface heat transfer coefficient; and (EVAPOTRANS) gives the ratio of actual evapotranspiration to potential evapotranspiration. Shading of the ground results from the use of the existing DOE-2.1B BUILDING-SHADE command.

A command called GROUND-WALL-MODEL describes the association of a ground structure and one or more spaces and applicable underground walls. Definition of the ground surface within the building coordinate system is accomplished through the keywords: HEIGHT, LENGTH, AZIMUTH, and TILT which are explained in the section containing the

examples. Additional keywords were also created for the existing DOE-2.1B UNDERGROUND-WALL and LAYERS commands. In the former case, the new information relates to geometric position (X, Y, Z, AZIMUTH) and wall boundary type (WALL-TYPE) which specifies whether the boundaries are ground, outside air or room air. The new keyword for the LAYERS command describes the type of surface being defined: NORMAL, UGWALL, or GROUND.

The basement configuration shown on Figure 3 can easily be modeled through the DOE-2.1B commands and keywords described above. One will observe the relative ease with which various earth contact configurations can be analyzed. The two step process used to create the finite element model is shown on Figure 4. Initially, the ground-wall model is separated into regions or blocks of constant thermal properties (as mentioned in step 6 in the previous section). In this example, three material properties are used; however, eleven blocks are generated. These eleven regions are subsequently divided into the grid structure representative of the finite element model. Mac Arthur's (1981) conclusions regarding increased accuracy with tighter spacing at the heat transfer boundaries are used in construction of the 130 nodes and 105 elements. Table 1 presents the data which the DOE-2.1B input processor transforms into response factors (only those data relevant to the underground structure have been listed). Firstly, the material properties of thickness, conductivity, density, and specific heat of individual layers of the room surfaces and ground are presented followed by the actual layers which describe the sequence of material layers. For this initial example, each surface has associated with it only one layer. Other keywords used with LAYERS are I-F-R, an abreviation for inside film resistance and TYPE which defines the type of surface and is used as a flag for logical control of the program flow. The CONSTRUCTION command specifies the construction characteristics of the surface which include the layers, absorptance, and surface roughness. The latter two parameters have been allowed to default and thus are not shown on Table 1. This command can only be used for NORMAL and UGWALL type layers. For TYPE equals GROUND, the GROUND-STRUCTURE command is used. Relevant keywords were discussed above and the values listed in the example actually are not necessary since they correspond to the default values. However, they are presented due to their importance to the ground contact modeling.

With the exception of the SPACE-CONDITIONS command and its associated keywords, which specify the internal conditions of the space, the remaining data relate to the geometry of the input configuration. The X, Y, Z, and AZIMUTH give position information of the space with respect to the building coordinate system and in the case of the underground surfaces with respect to the space coordinate system. The DOE-2.1B Reference Manual (Lawrence Berkeley Laboratory, 1980) should be consulted for more specific information regarding coordinate systems. The TILT specifies the angular position of each surface with repect to the vertical, i.e. 0° would imply that the surface is facing upward (usually a roof) and 90° means that the surface is vertical and facing a cardinal direction (usually an wall). Other keywords associated with the underground surfaces are self explanatory.

EXAMPLE OF USE

Figures 5, 6, and 7 present the relevant response factors for the above configuration. Also shown are results for two additional examples in which insulation has been added to the wall and floor. The insulation properties are listed on Table 1 and in each case the insulation is located between the concrete and ground. As previously stated in the algorithmic development, the second subscript represents the surface from which the response is obtained due to a triangular excitation on the surface represented by the first subscript. The ground surface response factor, X_{gg}, is the largest in magnitude and also the fastest in response (there being little delay since the excitation is on the ground surface). Also, the values of X_{gg} for each time increment are the same for all three configurations of the basement model. This indicates that the conditions at the wall and floor surface have a minimal effect at the ground surface. This fact, however, is not the situation with the other response factors. Figure 6 and 7 show the wall and floor surface response due to excitations at the ground surface and deep ground respectively. These figures yield very interesting information concerning the effect of the various surfaces on each other. For instance, the addition of floor insulation does not change the response at the wall due to a ground surface excitation, i.e. Y_{gw}. Likewise, the addition of wall insulation has a small effect on the floor response from a deep ground excitation, i.e. Y_{df}; whereas, wall insulation substantially increases the floor response from a ground surface excitation (Y_{gf}) and correspondingly, floor insulation increases the wall response from a deep ground excitation, Y_{dw}. These variations are related to the differing ground temperatures near the wall and floor. In the case of Y_{gf}, by adding wall insulation, the surrounding ground temperature has probably decreased which would tend to increase the loss through the floor. The same is true of Y_{dw}. Adding floor insulation decreases the surrounding temperature, thus increasing the loss through the wall.

The DOE-2.1B load calculation results for these models are presented on Figures 8 through 11. Weekly averaged outside air temperature and summed values of incident solar radiation on the ground surface are shown on Figures 8 and 9 respectively. These profiles, if represented analytically, would consists of a series of sinusoids at different amplitudes and frequencies. Their inclusion in this analysis stems from a desire to understand the transient nature of the heat losses through the wall and floor which are presented on Figures 10 and 11. The relationships established previously through the analysis of the response factors are also seen in the calculated loads. On Figure 10, the heat loss through the wall in the model with both wall and floor insulation is greater than the condition with only wall insulation. Figure 11 indicates that wall insulation increases the heat loss through the floor. The basement wall heat loss without insulation (Figure 10) is particularly revealing, especially when presented in the manner shown on Figure 12 (cross plot of wall heat loss and the difference in outside air temperature and the fixed space temperature of 20°C (68°F). The slope of a line drawn through the fifty-two data points represents an equivalent U-value, which in this case is approximately 2.07 W/m-°C (1.2 Btu/hr-ft-°F). This quantity is about equal to the value calculated by the method given in Chapter 25 in ASHRAE Fundamentals (1981); i.e. for a

2.13 m (7 ft) deep basement wall, the heat loss per unit length is 1.98 W/m-°C (1.15 Btu/hr-ft°F). Figures 13 and 14 present the basement wall heat loss for the configurartions in which insulation is used in the model. The slope is reduced dramatically reflecting the use of increased resistance. A heat loss value of approximately 0.345 W/m-°C (0.2 Btu/hr-ft-°F) is obtained for each case. This value compares with an extrapolated value (for R19 insulation) of the same order of magnitude obtained from the ASHRAE reference. Figure 15 is the summed heat flux for the uninsulated model for both the wall and floor as a function of the previous temperature difference. The shift in intersection is related to the influence of the deep ground temperature on the floor surface. A balance temperature of about 8.3°C (15°F) less than the 20°C (68°F) used above would yield zero heat loss. DOE-2.1B monthly results along with the annual heat loss are presented on Figure 16.

CONCLUSIONS

A major revision dealing with the analysis of earth contact structures such as basements, crawl spaces, slabs, and berms has been implemented within the structure of the DOE-2.1B energy analysis program. The major portions of the revisions were as follows: substantial DOE-2.1B input language changes which enable the definition of a detailed ground contact model; transformation of the input language model into a finite element model which is subsequently used to define a set of weekly response factors for those surfaces in contact with the ground; and addition of routines to the loads calculation portion of the DOE-2.1B code to calculate the ground contact heat gains and losses based on the defined set of response factors. This paper has presented a brief introduction to this new capability of DOE-2.1B. However, it should be noted that continued testing is being accomplished as well as implementation of additional capabilities which will inhance the overall operation of the code. The following paragraphs describe this remaining work:

(1) Earth contact library definition: Standardized sets of two-dimensional ground contact response factors representative of typical configurations will be made part of a library which will reduce the computer costs associated with the ground models. Also, users will have the ability to create their own libraries for future use.

(2) Parametric runs: The revisions, as they now stand, do not permit the use of the DOE-2.1B PARAMETER command which enables the running of parametric simulations. It is important, especially in cases in which response factor libraries are used, to give the user the flexibility of such analysis, both for economic reasons, as well as for simplification of the required DOE-2.1B input.

(3) Limits of configuration: The work involved is related to defining the limits of the two-dimensional configurations which users can confidently expect satisfactory results. This task involves extensive testing of the finite element construction algorithm and sufficient documentation to insure understandability.

(4) Verification of numbers: The DOE-2.1B output of response factors and heat flux quantities will be compared with other finite element or difference programs and verification of temperatures and fluxes with actual test data will also be accomplished.

The DOE-2.1B revisions discussed in this paper concern the analysis of a complicated multi-dimensional heat transfer problem through the use of a simplified input configuration definition and algorithmic technique. The ability to conveniently and accurately predict the heat flow phenomena in earth contact structures necessarily has a significant impact on the methodology used in other complicated heat conduction problems such as the analysis of edge effects, thermal bridges, internal/external surface interface due to thermal mass effects, etc. It is hoped that the work reported in this document proves to be a useful procedure in the analysis of these other areas of interest.

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TABLE 1 - BASEMENT MODEL DOE-2.1B INPUT

```
GROUND1       = MATERIAL
          TH=20.0        COND=0.982        DENS=114.0        S-H=0.275   ..
CONCRETE1     = MATERIAL
          TH=0.67        COND=0.636        DENS=140.0        S-H=0.210   ..
CONCRETE2     = MATERIAL
          TH=0.33        COND=0.636        DENS=140.0        S-H=0.210   ..
INSULATION1   = MATERIAL
          TH=0.33        COND=0.0167       DENS=1.5          S-H=0.382   ..

GND    = LAYERS     MAT=(GROUND1)     TYPE=GROUND    I-F-R=0.001    ..
BS1    = LAYERS     MAT=(CONCRETE1)   TYPE=UGWALL    I-F-R=0.68     ..
BS2    = LAYERS     MAT=(CONCRETE2)   TYPE=UGWALL    I-F-R=0.765    ..

     BSWALL  = CONSTRUCTION        LAYERS=BS1      ..
     BSFLOOR = CONSTRUCTION        LAYERS=BS2      ..

     GNDSTR  = GROUND-STRUCTURE          LAYERS=GND
               BARE-ALBEDO=0.2           SNOW-ALBEDO=0.9
               BARE-ROUGHNESS=0.0038     SNOW-ROUGHNESS=0.0002
               EVAPOTRANS=1.0            DEEP-GROUND-TEMP=47.5    ..

SC1 = SPACE-CONDITIONS    ZONE-TYPE=CONDITIONED    TEMPERATURE=(68)    ..

BASEMENT = SPACE
           X=0    Y=0    Z=-8    AZIMUTH=0    AREA=14    VOLUME=112
           SPACE-CONDITIONS=SC1    ..

     SWBSM = UNDERGROUND-WALL
           X=0    Y=0    Z=0     AZIMUTH=180    TILT=90
           HEIGHT=8    WIDTH=1    CONSTRUCTION=BSWALL    ..
     FLBSM = UNDERGROUND-FLOOR
           X=0    Y=14   Z=0     AZIMUTH=180    TILT=180
           HEIGHT=14   WIDTH=1    CONSTRUCTION=BSFLOOR   ..

GWM-S = GROUND-WALL-MODEL
        HEIGHT=0    DEPTH=20    LENGTH=34    TILT=0
        GROUND-STRUCTURE=GNDSTR
        SPACE1=BASEMENT
        WALLS1=(SWBSM,FLBSM)    ..
```

Figure 1

Wall Section Showing Coordinate System for Response Factors

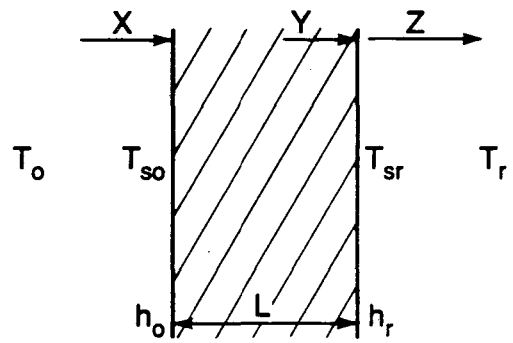

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Figure 2

Response Factor Representation of Basement Model

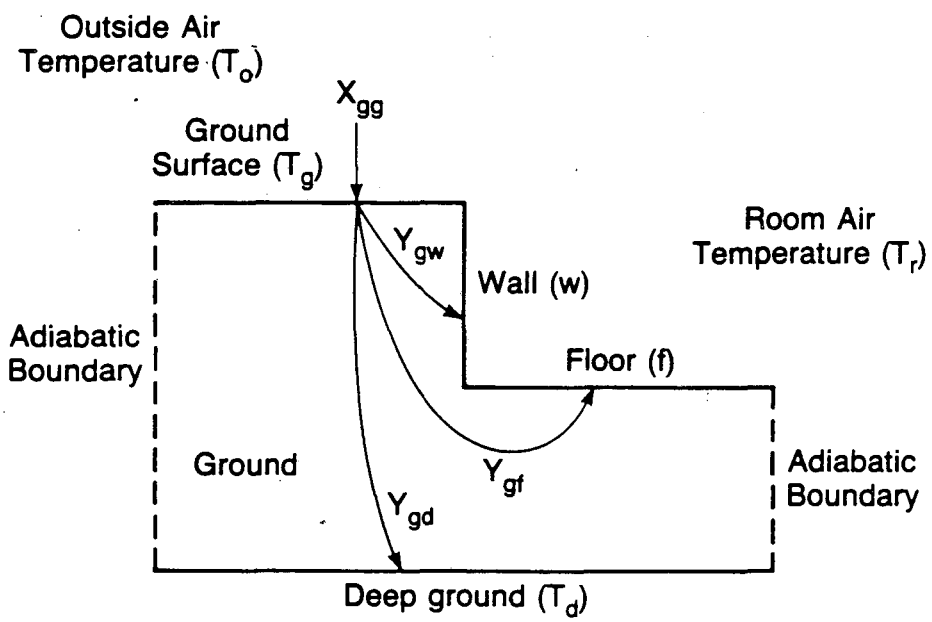

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Figure 3

Basement Configuration Unit Width

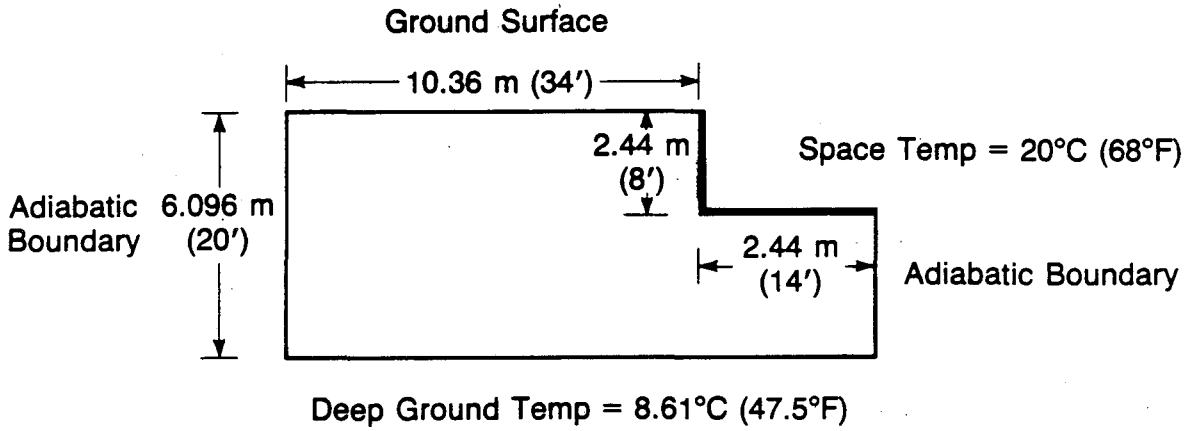

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Figure 4

Finite Element Definition of Basement Configuration

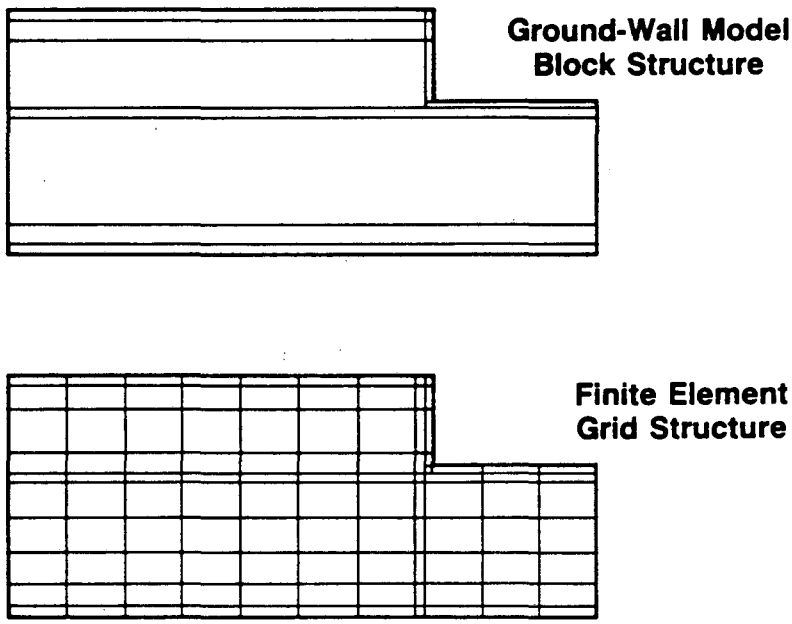

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Figure 5

Ground Surface Response Due to Triangular Temperature Excitation on Ground Surface

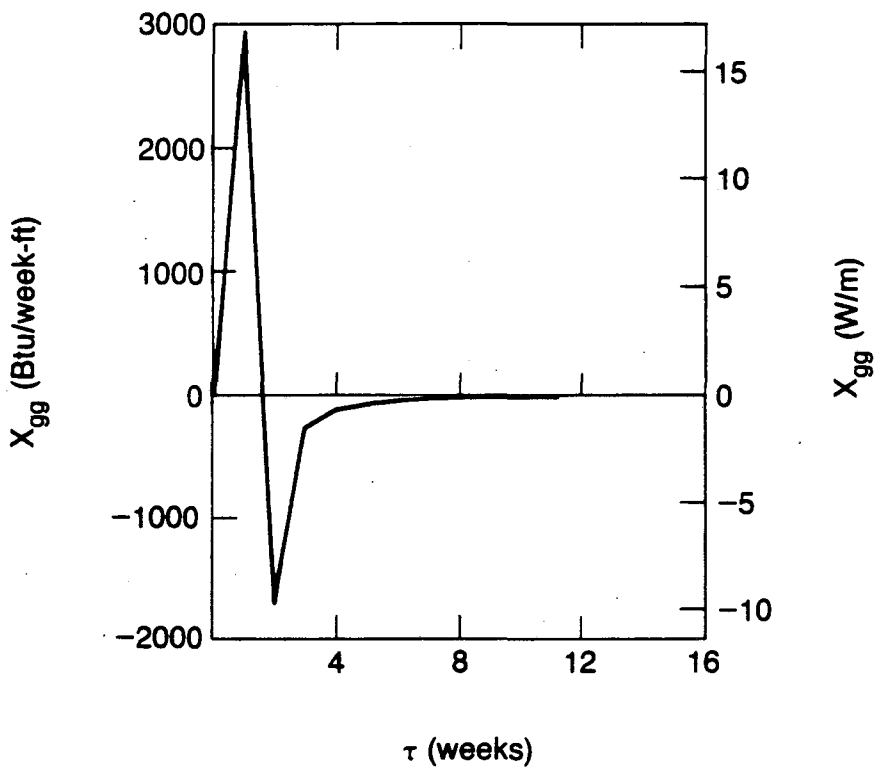

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Figure 6

Wall and Floor Response Due to Triangular Temperature Excitation at Ground Surface

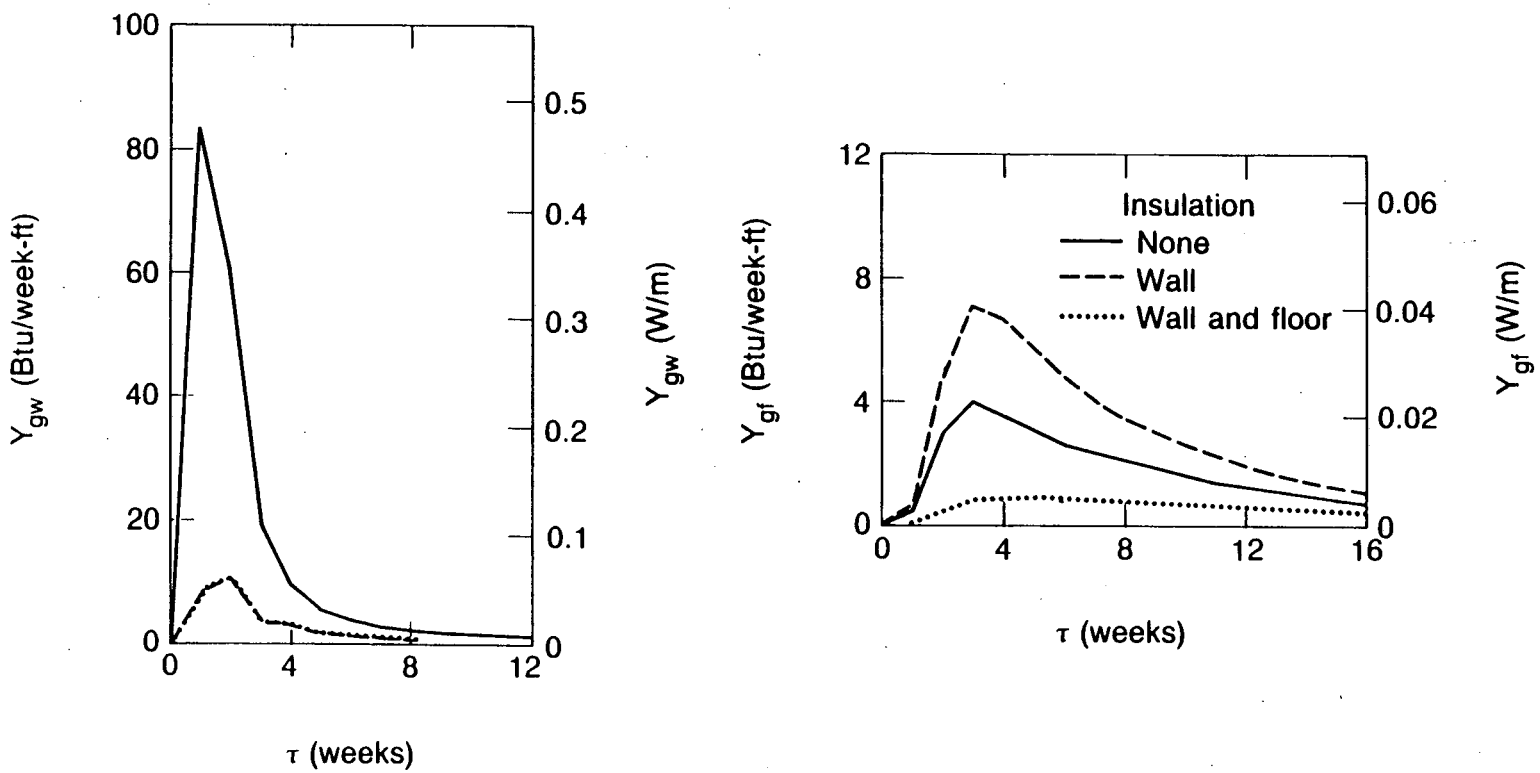

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Figure 7

Wall and Floor Response Due to Triangular Temperature Excitation at Deep Ground

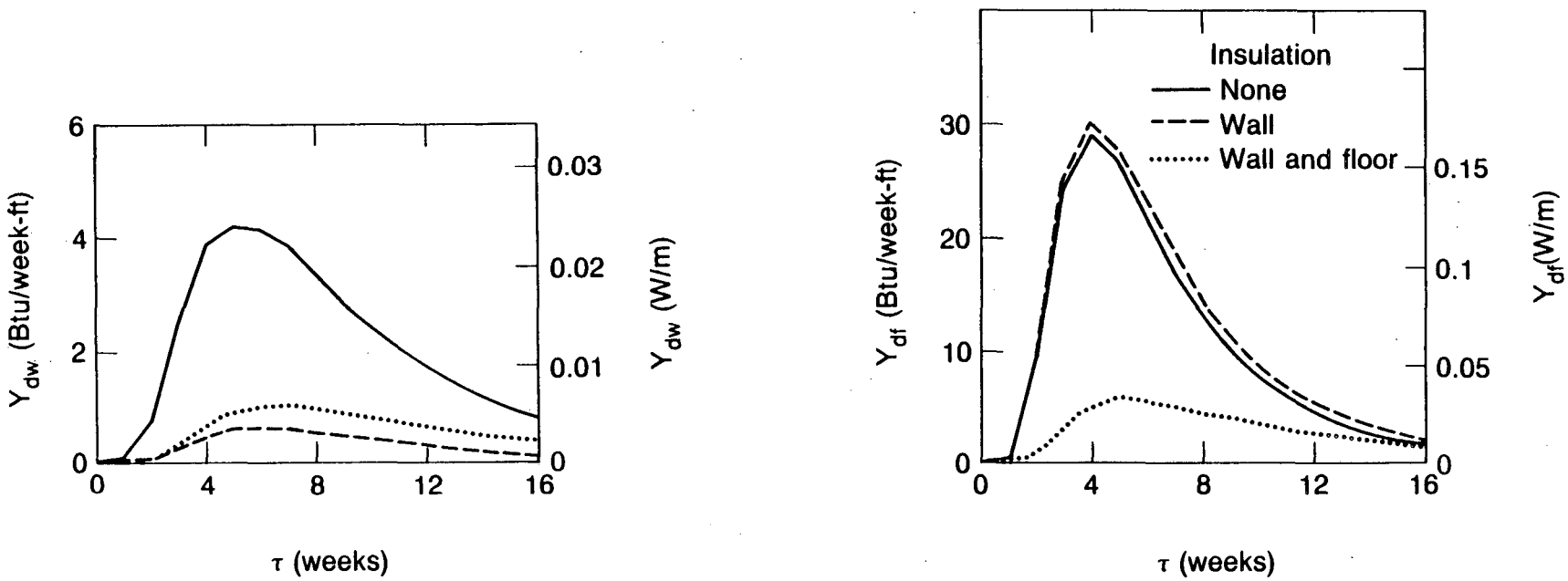

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Figure 8

Weekly Averaged Outside Air Temperature
Madison WI, WYEC

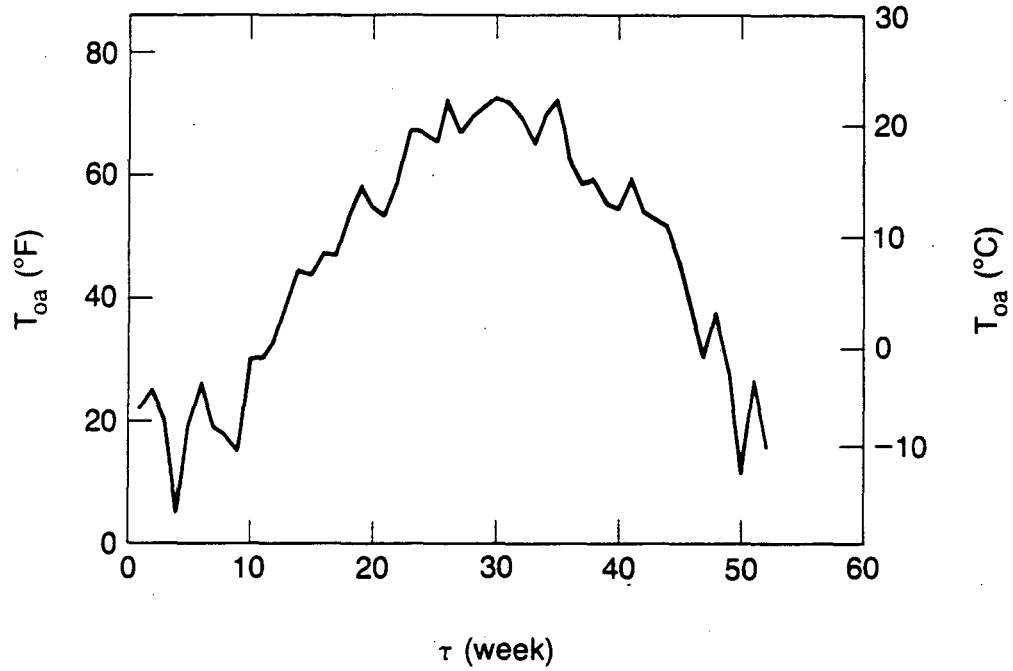

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Figure 9

Weekly Summed Incident Solar Radiation
on Ground Surface
Madison, WYEC

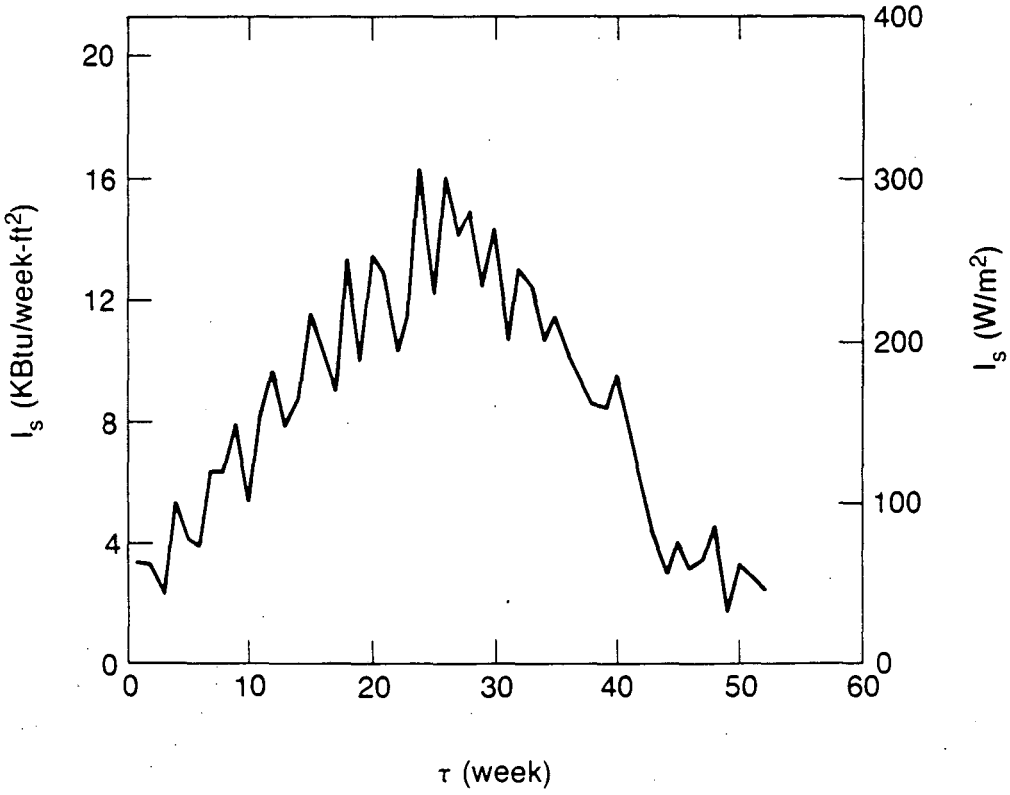

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Figure 10

Hourly Heat Loss Through Basement Wall

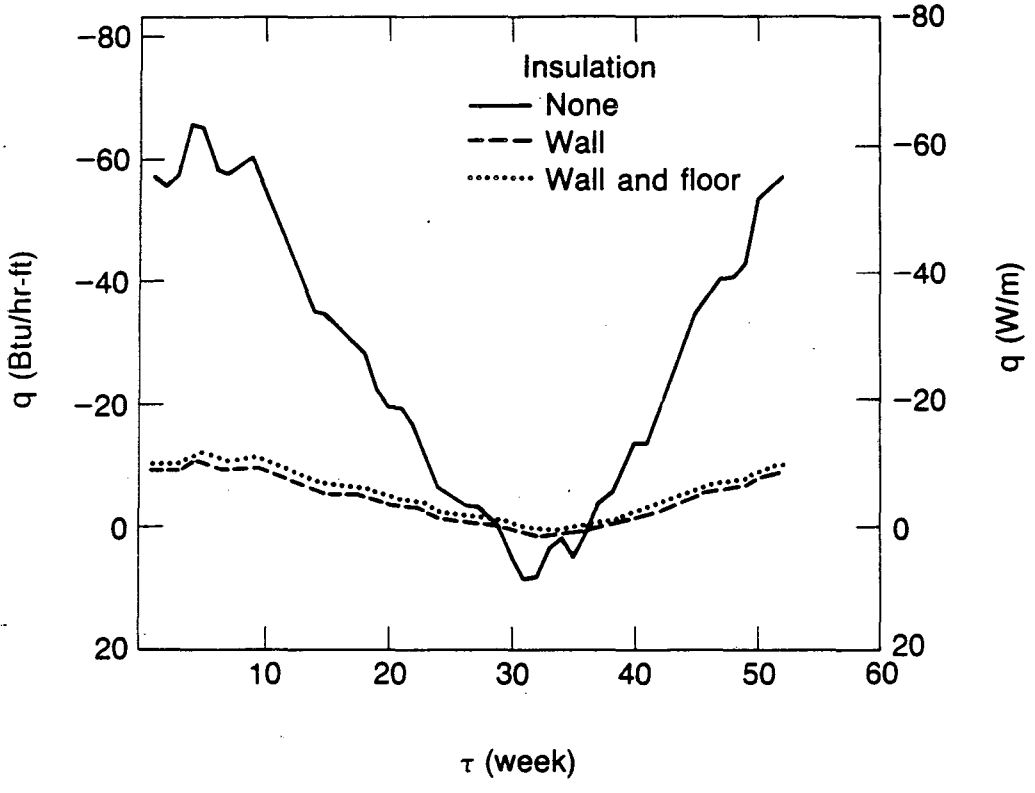

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Figure 11

Hourly Heat Loss Through Basement Floor

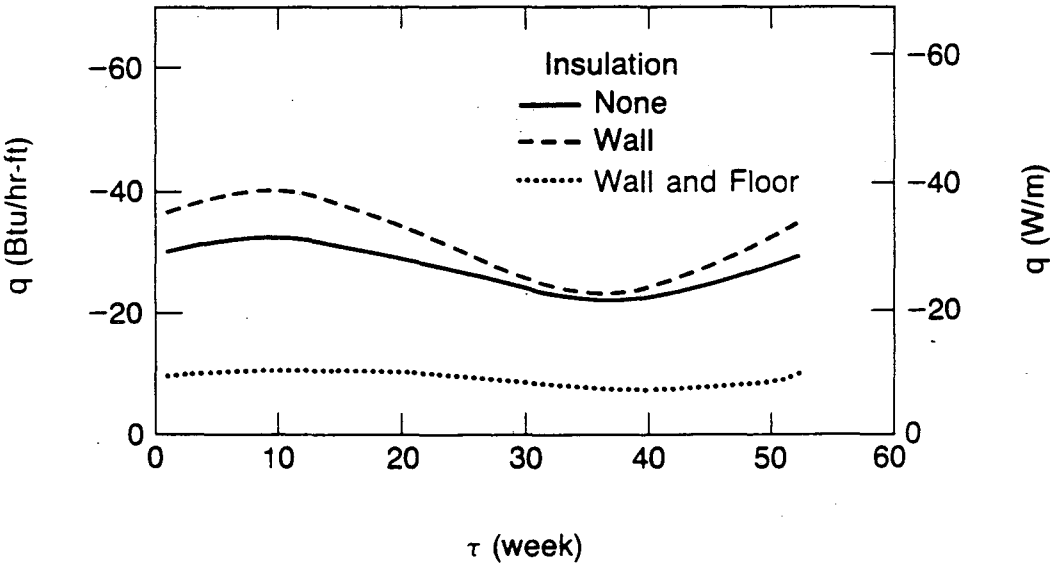

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Figure 12 **Hourly Heat Loss Through Basement Wall vs Temperature Difference Between Outside Air and Room Air Uninsulated Wall and Floor**

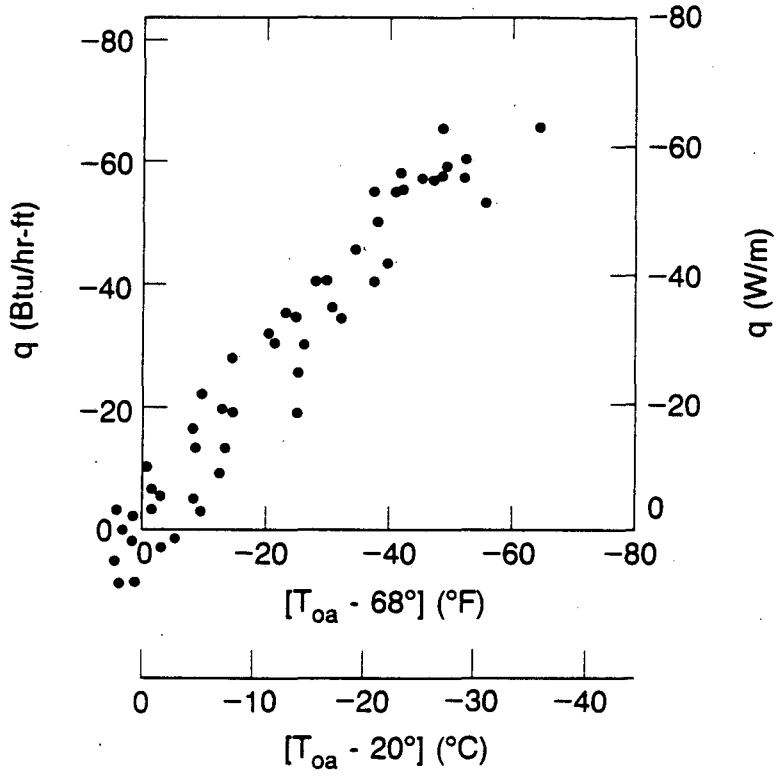

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Figure 13 **Hourly Heat Loss Through Basement Wall vs Temperature Difference Between Outside Air and Room Air Insulated Wall, Uninsulated Floor**

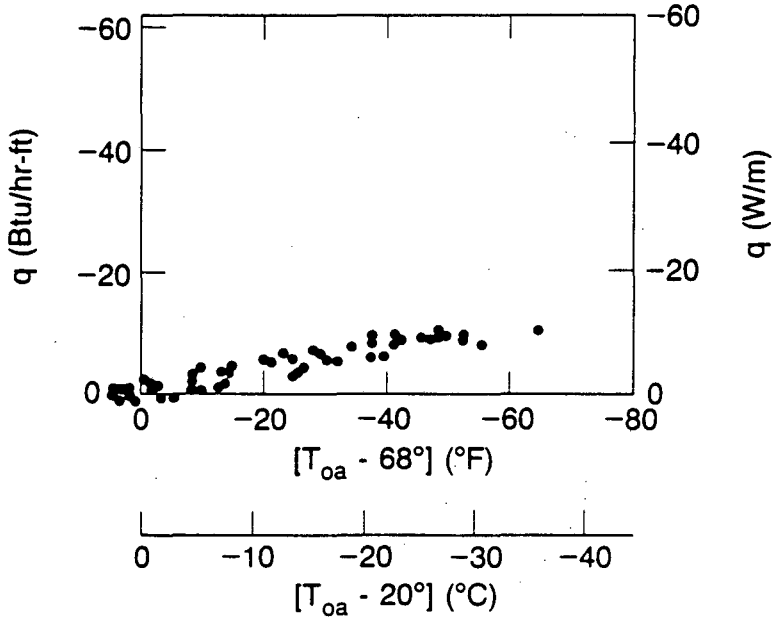

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Figure 14 **Hourly Heat Loss Through Basement Wall vs Temperature Difference Between Outside Air and Room Air Insulated Wall and Floor**

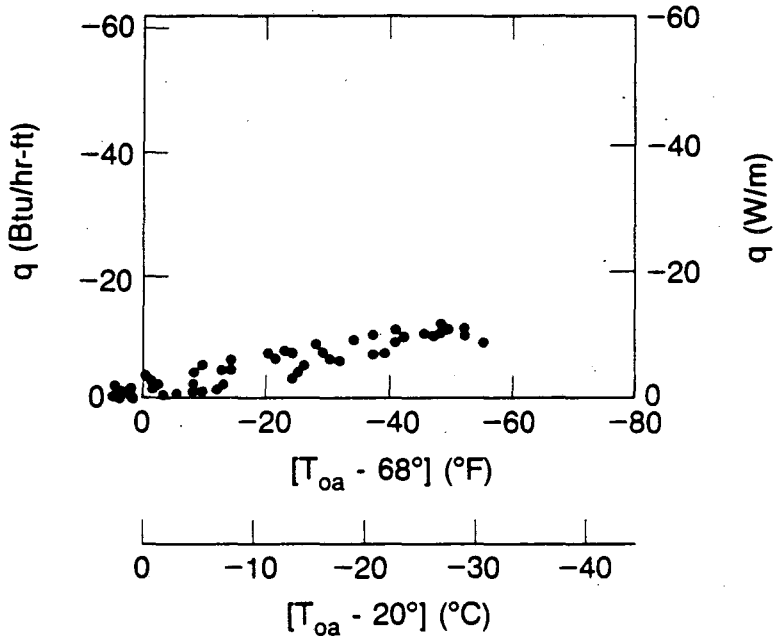

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Figure 15 **Hourly Heat Loss Through Basement Wall and Floor vs Temperature Difference Between Outside Air and Room Air Uninsulated Wall and Floor**

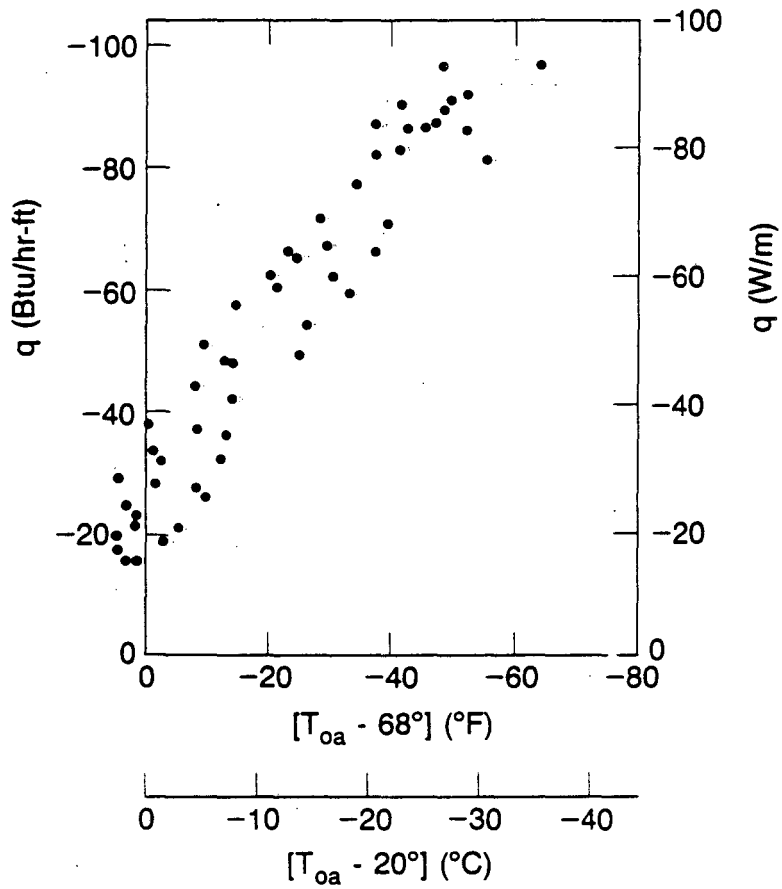
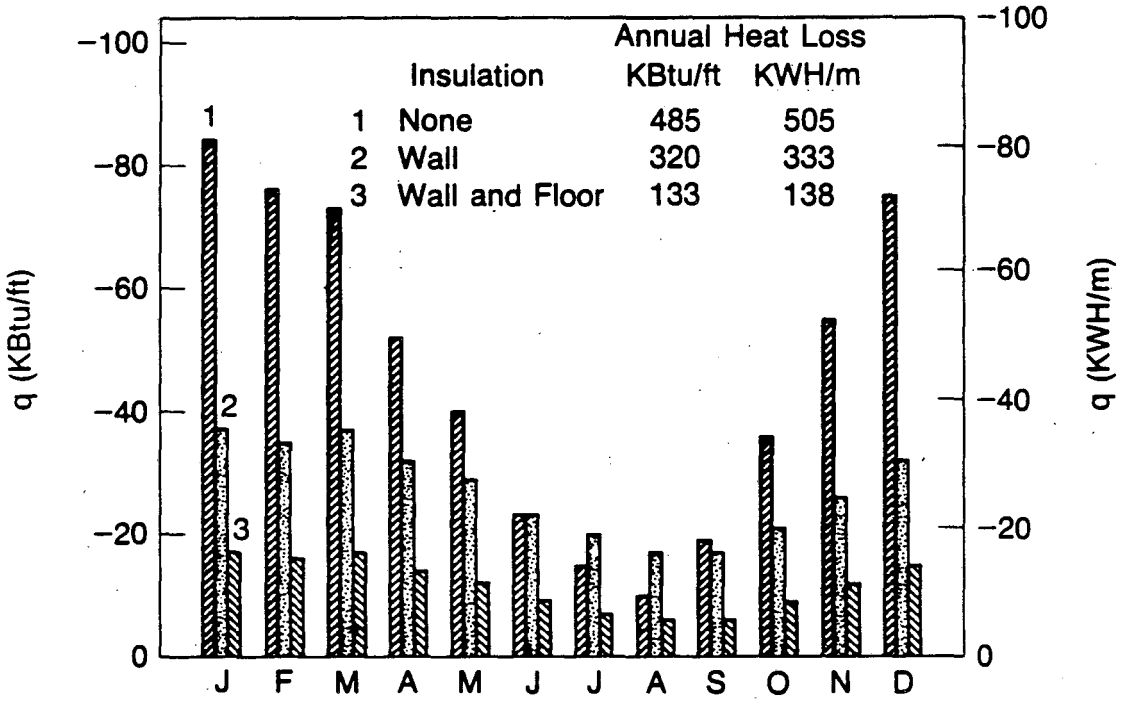


Figure 16

Monthly Heat Loss Through Basement Wall and Floor



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