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PASSIVE SOLAR CALCULATION METHODS

Interim Report

April 15, 1979

Work Performed Under Contract No. EM-78-C-01-5221

CCB/Cumali Associates
Oakland, California

U.S. Department of Energy

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Solar Energy

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B. Amy Steels
Authorizing Official

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2930 LAKESHORE AVENUE, OAKLAND, CALIFORNIA 94610 (415) 465-0511

APRIL 15, 1979

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PROJECT IDENTIFICATION

This report details the work accomplished to date under contract number EM-78-C-01-5221, Development of Passive Solar Calculation Methods. It is the first in a series of reports and encompasses the period from October 15, 1978 through March 15, 1979. Because of the interrelationships among the various tasks as outlined in the Statement of Work (see Appendix H.5), this report discusses results within each of the following tasks:

1. TASK 1 - Evaluation of Existing Analysis Techniques
2. TASK 2 - BLAST/DOE-1 Program Interface and Comparison with BR-202
3. TASK 3 - Development of Analytic Relationships Between the Thermal Balance and Weighting Factor Techniques.

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A. INTRODUCTION

Within the immediate future, Passive Solar design techniques will become an important part of the architectural community's resources. The critical nature of fossil fuel supplies and the uncertain effects of present day nuclear technology make it imperative that alternative energy sources be utilized. However, prior to Passive Solar methods becoming a reality, as with any new development, certain initial steps must be taken to isolate those factors which directly influence the feasibility of such methods. This report documents a portion of the current work being done in Passive Solar research and development under Department of Energy Contract number EM-78-01-5221, Development of Passive Solar Calculation Methods.

The Statement of Work for this contract is listed in Appendix 4. Five specific tasks were identified as part of the study as follows:

1. Evaluation of Existing Analysis Techniques
2. BLAST/DOE-1 Program Interface and Comparison with BR-202
3. Development of Analytic Relationships Between the Thermal Balance and Weighting Factor Techniques
4. Development and Evaluation of Alternative Analysis Techniques
5. Multiple Thermal Zone Analysis

This report is the first in a series and details the results accomplished under Tasks 1, 2, and 3 above. Initially, the various methods available for use in thermal load analysis are presented with detailed information on algorithms used in the thermal balance and weighting factor techniques.

One of the primary sources of actual test data for thermal analysis is the LASL test cell. Both LBL and LASL are currently utilizing this data for a variety of purposes. To establish a base for subsequent analysis

and also to coordinate the objectives in this contract with past and/or future passive solar analysis, a comparison is presented of the thermal loads calculated by BLAST and the Department of Energy Program - DOE-1. Whereas BLAST uses the thermal balance method, DOE-1 calculates loads by the weighting factor technique. A large part of this study deals with the weighting factor concept and therefore the differences in generated loads must be quantified.

Future developments within the scope of this contract are next discussed to include recommendations for further analysis.

Specific discussions of the aforementioned computer programs, BR202, BLAST and DOE-1, are contained in the Appendix. The purpose was to identify, in a limited manner, the relative differences in thermal load calculation techniques at a program specific level so that the presentation in section B would, by itself, be general nature.

B. THERMAL LOAD CALCULATION TECHNIQUES

Within this section are detailed the algorithms used by the thermal balance and weighting factor methods of determining space thermal loads. Also a brief discussion is given on the thermal network type of solution. Heating/cooling loads are calculated by summing the heat gain/loss components due to conduction, convection and radiation. The approach used in the thermal balance scheme is one which performs a heat balance at both the inside and outside surfaces of the walls enclosing the space from which inside surface and space air temperatures are determined. The resultant load is then simply found relating these temperatures with an infiltration and/or heating/cooling ventilation system inputs. The weighting factor technique was developed primarily because a matrix solution to the heat balance equations would not be necessary and thus computer execution time would be reduced. Predefined "weighting factors" are first convolved with the component heat gains at constant space temperature to determine a base load distribution. The variation in space air temperature is then found by an additional convolution with another set of weighting factors. The predefined weighting factors are generated by solving the heat balance matrix for a unit pulse heat gain input. The thermal network procedure represents heat transfer processes through the use of regions of uniform temperature distribution. Each region or node is defined by a combination of conductance, capacitance and heat source parameters. Node temperature fluxuations are determined by solving a heat balance expression at each node.

1. THERMAL BALANCE

The thermal balance method of load calculations employs a heat balance on each surface within the space to determine surface and/or room temperatures from which the resultant heating/cooling load is determined. The analysis discussed herein is similar to the development outlined in References 2 and 5 in which the heat gain at any one surface by conduction is balanced by the convective heat transfer between the surface and the room, the radiant heat gain due to emission from the other surfaces and the radiant gain due to other sources such as transmitted solar radiation, radiation from equipment and occupants within the space, etc. Initially, the constant room air temperature equations are developed after which the variable room air temperature case is derived.

(a) Surface Temperature Heat Balance

Consider the diagram below, where a heat balance is performed on an external wall enclosing a space:

The general equation for heat balance at any internal surface, i , takes the form:

$$q_{K_i}(t) = q_{C_i}(t) + q_{RS_i}(t) + q_{R_i}(t) \quad (B.1.1)$$

where

- $q_{K_i}(t)$ = heat gain by conduction at surface i at time t
 $q_{C_i}(t)$ = heat gain by convection at surface i at time t
 $q_{RS_i}(t)$ = heat gain by radiant emission from other surfaces at surface i at time t
 $q_{R_i}(t)$ = heat gain by radiation from other sources at surface i at time t

(1) Conductive Heat Gain

The conductive heat gain, $q_{K_i}(t)$, relates the outside and inside surface temperatures through the use of response factors applied to a time series of past values of temperatures:

$$q_{K_i}(t) = \left[\sum_{j=0}^{n_i} x_i(j) T_i^I(t-j) - \sum_{j=0}^{n_i} y_i(j) T_i^O(t-j) \right] A_i + C_i \cdot q_{K_i}(t-1) \quad (B.1.2)$$

where

- $x_i(j)$ = internal surface time series response factors for surface i
 $y_i(j)$ = cross surface time series response factors for surface i
 A_i = surface area of surface i
 C_i = common ratio for the above response factors
 n_i = number of response factor terms in the above time series
 $T_i^I(t-j)$ = inside surface temperature history of surface i
 $T_i^O(t-j)$ = outside surface temperature history of surface i

(2) Convective Heat Gain

The convective heat gain, $q_{C_i}(t)$, can be expressed as:

$$q_{C_i}(t) = h_i A_i [T_R - T_i^I(t)] \quad (B.1.3)$$

where

- h_i = convective heat transfer coefficient which is dependent on the directions of heat flow
 T_R = room air temperature, which in this derivation is assumed constant

(3) Radiant Heat Gain From Other Surfaces

The radiant heat gain due to emission from other surfaces, $q_{RS_i}(t)$, within the space is:

$$q_{RS_i}(t) = A_i \sum_{m=1}^{NS} G_{i,m} [T_m^I(t) - T_i^I(t)] \quad (B.1.4)$$

where

- NS = number of surfaces within the space
- $T_m^I(t)$ = inside surface temperature of surface m at time t
- $G_{i,m}$ = a term relating the heat exchange between surfaces i and m

$G_{i,m}$ can be expressed as:

$$G_{i,m} = 4E_i F_{i,m} \sigma T_{REF}^3 \quad (B.1.5)$$

where

- E_i = emissivity of surface i
- $F_{i,m}$ = radiation view factor between surfaces i and m
- σ = Stefan-Boltzmann constant
- T_{REF} = reference temperature

The radiation view factor, $F_{i,m}$, takes the form:

$$F_{i,m} = \frac{1}{A_i} \int_{A_i} \int_{A_m} \cos \phi_i \cdot \cos \phi_m dA_i dA_m \quad (B.1.6)$$

where ϕ_i , ϕ_m and r^2 represent geometrical relationships between the surfaces, (see References 12 and 13).

(4) Radiant Heat Gain From Other Sources

The radiant gain from other sources, q_{R_i} , is a summation involving solar radiation quantities, equipment, occupants, and lights.

$$q_{R_i}(t) = q_{S_i}(t) + f_e q_e(t) + f_o q_o(t) + f_L q_L(t) \quad (B.1.7)$$

where

- $q_{S_i}(t)$ = radiation from the sun at surface i at time t
- $q_e(t)$ = radiation from equipment on surface i at time t

$q_o(t)$ = radiation from occupants on surface i at time t
 $q_L(t)$ = radiation from lights on surface i at time t
 f_e, f_o, f_L = the fraction of heat gain which is radiative

Substitution of each of the above components into equation (B.1.1) yields:

$$\left[\sum_{j=0}^{n_i} x_i(j) T_i^I(t-j) - \sum_{j=0}^{n_i} y_i(j) T_i^O(t-j) \right] A_i + C \cdot q_{K_i}(t-1) = \quad (B.1.8)$$

$$h_i A_i [T_R - T_i^I(t)] + A_i \sum_{m=1}^{NS} G_{i,m} [T_m^I(t) - T_i^I(t)] + q_{R_i}(t)$$

Isolating the inside surface temperatures at time t gives:

$$\begin{aligned} A_i \left[x_i(0) + h_i + \sum_{m=1}^{NS} G_{i,m} \right] T_i^I(t) - A_i \left[\sum_{m=1}^{NS} G_{i,m} \right] T_m^I(t) = \\ A_i \left[- \sum_{j=1}^{n_i} x_i(j) T_i^I(t-j) + \sum_{j=0}^{n_i} y_i(j) T_i^O(t-j) \right] \\ - C \cdot q_{K_i}(t-1) + q_{R_i}(t) + h_i A_i T_R \end{aligned} \quad (B.1.9)$$

This equation represents the form used for the constant room temperature case. With variable room temperature, an additional equation must be defined.

(b) Room Air Heat Balance

The room air heat balance is obtained by considering the effects of surface temperature changes, infiltration and supply mass flow rates, and convection heat gain due to other sources such as equipment, lights, and occupants within the space. The general equation takes the form:

$$q_{CS}(t) + q_{FL}(t) + q_{SP}(t) + q_{CO}(t) = 0 \quad (B.1.10)$$

where

$q_{CS}(t)$ = total convective gain due to surface temperature changes
 $q_{FL}(t)$ = heat gain by infiltration
 $q_{SP}(t)$ = heat gain by supply air system
 $q_{CO}(t)$ = convective heat gain from other sources

(1) Convective Gain Due to Surface Temperatures

The total convective heat gain due to surface temperature changes is:

$$q_{CS}(t) = \sum_{i=1}^{NS} h_i A_i [T_i^I(t) - T_R(t)] \quad (B.1.11)$$

where

$T_R(t)$ = room air temperature at time t

(2) Heat Gain Due to Infiltration

The heat gain from the infiltration of outdoor air, $q_{FL}(t)$, can be expressed as:

$$q_{FL}(t) = m_{FL}(t) C_p [T_o(t) - T_R(t)] \quad (B.1.12)$$

where

$m_{FL}(t)$ = mass flow rate at time t

C_p = specific heat of air

$T_o(t)$ = outdoor dry bulb temperature at time t

(3) Heat Gain Due to Supply Air

The heat gain due to supply air, $q_{SP}(t)$, is the same form as the infiltration gain above:

$$q_{SP}(t) = m_{SP}(t) C_p [T_S(t) - T_R(t)] \quad (B.1.13)$$

where

$m_{SP}(t)$ = mass flow rate at time t

$T_S(t)$ = supply air temperature at time t

(4) Convective Gain From Other Sources

The convective gain from other sources, $q_{CO_L}(t)$, can be written as follows:

$$q_{CO}(t) = f_{ec} q_{ec}(t) + f_{oc} q_{oc}(t) + f_{LC} q_{LC}(t) + q_{bb}(t) + q_{sh}(t) \quad (B.1.14)$$

where

$$\begin{aligned}
 q_{ec}(t) &= \text{convective component due to equipment at time } t \\
 q_{oc}(t) &= \text{convective component due to occupants at time } t \\
 q_{LC}(t) &= \text{convective component due to lights at time } t \\
 q_{bb}(t) &= \text{baseboard load at time } t \\
 q_{sh}(t) &= \text{solar energy absorbed by interior shades and convected directly into the space at time } t \\
 f_{ec}, f_{oc}, f_{LC} &= \text{fraction of heat gain which is convective}
 \end{aligned}$$

The above f terms are related to the radiation f terms as follows:

$$f_{ec} = 1. - f_e \quad (B.1.15)$$

Substitution of the above component expressions into equation (B.1.10) yields:

$$\begin{aligned}
 \sum_{i=1}^{NS} h_i A_i \left[T_i^I(t) - T_R(t) \right] + m_{FL}(t) C_P \left[T_O(t) - T_R(t) \right] \\
 + m_{SP}(t) C_P \left[T_S(t) - T_R(t) \right] + q_{CO}(t) = 0
 \end{aligned} \quad (B.1.16)$$

Rearranging terms to isolate the room air temperature gives:

$$\begin{aligned}
 \sum_{i=1}^{NS} h_i A_i T_i^I(t) + \left[- \sum_{i=1}^{NS} h_i A_i - m_{FL}(t) C_P - m_{SP}(t) C_P \right] T_R(t) = \\
 - m_{FL}(t) C_P T_O(t) - m_{SP}(t) C_P T_S(t) - q_{CO}(t)
 \end{aligned} \quad (B.1.7)$$

Equations B.1.9 and B.1.17, when combined and put in matrix form results in:

$$\begin{bmatrix} C_{1,1} & C_{1,2} & C_{1,3} & \cdots & C_{1,NS+1} \\ C_{2,1} & . & . & . & C_{2,NS+1} \\ C_{3,1} & . & . & . & . \\ . & . & . & . & . \\ . & . & . & . & . \\ . & . & . & . & . \\ C_{NS+1,1} & . & . & . & C_{NS+1,NS+1} \end{bmatrix} \begin{bmatrix} T_1^I(t) \\ T_2^I(t) \\ . \\ . \\ . \\ . \\ T_R(t) \end{bmatrix} = \begin{bmatrix} B_1 \\ B_2 \\ . \\ . \\ . \\ . \\ B_{NS+1} \end{bmatrix} \quad (B.1.18)$$

where

$$\begin{aligned}
 C_{i,i} &= A_i \left[X_i(0) + h_i + \sum_{m=1}^{NS} G_{i,m} \right] \\
 C_{i,m} &= -A_i G_{i,m} = C_{m,i} = -A_m G_{m,i} \\
 C_{i,NS+1} &= -h_i A_i = C_{NS+1,m} = -h_m A_m \\
 C_{NS+1,NS+1} &= -\sum_{i=1}^{NS} h_i A_i - m_{FL}(t)C_p - m_{SP}(t)C_p
 \end{aligned}$$

and

$$\begin{aligned}
 B_i &= A_i \left[-\sum_{j=1}^{n_i} X_i(j) T_i^I(t-j) + \sum_{j=0}^{n_i} Y_i(j) T_i^O(t-j) \right] \\
 &\quad - C \cdot q_{K_i}(t-1) + q_{R_i}(t) \\
 B_{NS+1} &= -m_{FL}(t)C_p T_o(t) - m_{SP}(t)C_p T_s(t) - q_{CO}(t)
 \end{aligned}$$

(c) Zone Load Calculation

Once the surface temperature and room air temperatures are known, the zone load can be obtained as follows:

$$Q(t) = \sum_{i=1}^{NS} h_i A_i \left[T_i^I(t) - T_R(t) \right] + m_{FL}(t)C_p \left[T_o(t) - T_R(t) \right] + q_{CO}(t) \quad (B.1.19)$$

which is the same expression as equation (B.1.17), since the zone load is defined as "...the heat picked up by the room air (or that lost by the room air) which has to be removed (or added) by the central air conditioning system."¹

¹Reference 5, page 111.

2. WEIGHTING FACTORS

The weighting factor concept used in determining zone loads is based on the work of G. P. Mitalas and D. G. Stephenson of the National Research Council of Canada (References 1 and 2). Instead of solving a set of heat balance equations, as in the previous section, in which the zone load was determined by explicit solution of surface and room temperatures, each component of the heat gain contributing to the total load is solved for by using a pre-tabulated set of "weighting factors." Each component of heat gain is calculated independent of the others. For example, the heat gain resulting from a wall section is related to room temperature by using a combined convection/radiation coefficient; thus the radiation coupling among surfaces is made implicit. The component heat gains are then weighted to estimate their contribution to the space load.

The weighting factor method is based on the assumption that the superposition principle applies to heat transfer process occurring in a space, i.e., that the thermal processes can be described by linear differential equations. Therefore, one can use Green's Function solutions to represent the time behavior of heat transfer within the space. This, in effect, means that one may calculate the heat gain due, for example, to solar energy independent of the other heat gains. A unit pulse is applied to the right hand side of the matrix equation (B.1.18) from which is obtained the time history of the resulting loads, $r_i(t)$. The solution for any arbitrary input, $q_i(t)$, is then found by convolution with $r_i(t)$:

$$Q_i(t) = \sum_{j=0}^{\infty} q_i(t-j)r_i(j)$$

Thus the weighting factors correspond to the values of the Green's Function solution of the room thermal balance equations.

The important point to be realized is that the basis of the thermal balance and weighting factor techniques is the same. In effect, they are two distinct methods of solving the same set of balance equations. Given identical

inputs, the resultant solutions obtained will be identical for a given space. The reason for whatever differences exist between the results of these two techniques is due to the use of a series of pretabulated set of weighting factors which are applied to spaces that in many cases are not similar to the reference space from which the factors were derived. A concentrated study within the scope of work of this contract has taken place to develop techniques which allow the calculation of specific weighting factors for any space and therefore generate solutions identical to the thermal balance method. Section C discusses the results of this study.

The remaining portion of this section will treat the basic components of heat gain due to conduction, convection and radiation which contribute to the zone load at constant room temperature; after which, the room air temperature variation equations are discussed. In addition, two methods of weighting factor development are discussed herein: one details the weighting factor concept using an algebraic convolution scheme; and the other uses Z-transform analysis techniques.

(a) Constant Zone Temperature Load

The weighting factor concept provides a relationship between the heat gain components due to conduction, convection and radiation and the total zone load. Normally, a load at constant room temperature is first computed using weighting factors for each of the above components. The variation in zone temperature is then derived from the computed zone load and an additional set of air temperature weighting factors.

(1) Conductive Heat Gain

The conductive heat gain, $q_{K_i}(t)$, is calculated using an equation of the form:

$$q_{K_i}(t) = - \left[\sum_{j=0}^{n_i} Y_i(j) T_i^0(t-j) \right] A_i + C_i \cdot q_{K_i}(t-1) \quad (B.2.1)$$

where

$Y_i(j)$ = cross surface time series response factors for surface i

A_i = surface area of surface i

C_i = common ratio for the above response factors

n_i = number of response factor terms in the above time series

$T_i^0(t-j)$ = outside surface temperature history of surface i

The outside surface temperature history, $T_i^0(t-j)$, is generated by a heat balance at the outside surface relating the conduction equation to the heat gain by solar radiation incident on the surface. The response factor effect of the inside surface temperature ($T_i^I(t-j)$ in equation B.1.2) is dealt with by an additional layer of resistance in both equation (B.2.1) above and the outside surface temperature calculations.

For a surface which is not delayed, the heat gain is defined as:

$$q_{K_i}(t) = U_i [T_{SOL} - T_R] A_i \quad (B.2.2)$$

where

U_i = heat transfer coefficient of surface i

T_{SOL} = sol-air temperature

T_R = zone temperature

(2) Convective Heat Gain

The convective heat gain is computed directly for each source. Reference 6 provides techniques for calculating the magnitude of this component due to equipment, occupants and infiltration.

Usually a specific magnitude is calculated or a percent convective gain is determined.

(3) Radiative Heat Gain

The previous statement regarding convective heat gain is also valid here. Solar radiation quantities, both transmitted and absorbed, are necessary for proper definition of radiative heat gain in addition to contributions arising from lights, equipment, occupants and infiltration.

(4) Zone Load Calculation

Once the component heat gains are known, the zone load component at constant space temperature is calculated using a set of predefined weighting factors as follows:

$$Q(t) = V_0 q(t) + V_1 q(t-1) - W_1 Q(t-1) \quad (B.2.3)$$

where

$Q(t)$ = component zone load at time t

V_0, V_1, W_1 = weighting factors

$q(t)$ = heat gain component at time t

$q(t-1)$ = heat gain component at time $(t-1)$

$Q(t-1)$ = component zone load at time t

The total load is simply the summation of all component loads.

(b) Zone Air Temperature Variation

The space air temperature variation in its simplest form (i.e., without infiltration and ventilation or extraction quantities) is calculated by an expression which relates the change in air temperature to the previously calculated load, i.e.,

$$\sum_{j=0}^{\infty} P_j [Q(t-j) - q(t-j)] = \sum_{j=0}^{\infty} G_j [T_R(t-j) - T_{RC}] \quad (B.2.4)$$

The G's and P's are obtained by application of a pulse in room temperature, T_R , which corresponds to a heat addition similar to the pulse discussed previously for heat gain. Convolution of the resultant weighting factors with any arbitrary time history of either heat extraction/addition or temperature yields the resulting space temperature distribution. Certain corrections must be applied to the formulation for infiltration and conductance quantities. The magnitude of the infiltration is based on both outside air temperature and inside space temperature; thus as room temperature changes, the G terms must be corrected. Using equation (B.2.4) the correction would be:

$$G_i(t) = G_i + 1.1 \text{ cfm } P_i \quad (\text{B.2.5})$$

As the zone temperature changes from T_{RC} to some other value, the overall conductance does also; thus using an analysis similar to that for infiltration, the resulting G factors would be:

$$G_i(t) = G_i + P_i \left[1.1 \text{ cfm} + \sum_{i=1}^{NS} U_i A_i \right] \quad (\text{B.2.6})$$

where

U_i = overall U-value for surface i

A_i = surface area of surface i

The use of $\sum U_i A_i$ for conductance is correct in the asymptotic case but for sudden fluxuations in temperature, it is likely to be an underestimate. This effect will be analyzed during the subsequent portion of the contract.

The validity of the weighting factor approach stems from an analysis of the load response to a unit excitation in heat gain and zone air temperature. The development that follows describes both an algebraic convolution scheme and a Z-transform method for relating the load to previously computed weighting factors. The thermal balance equations described in Section B.1 were used in the past (see Appendix H.2) to define the component weighting

factors discussed previously. The equations were solved for various unit excitations and the resultant load profiles were convolved in a manner similar to the techniques described below. This was the approach used for definition of the ASHRAE pretabulated weighting factors.

(c) Algebraic Convolution Method

The weighting factor technique used in calculating the total load is similar to the method employed in defining response factors, which is the well known procedure used in analyzing conduction heat transfer. Basically, the cooling/heating load at any time t is related to the input heat gain/loss by an expression of the form:

$$Q(t) = \sum_{j=0}^{\infty} r(j)q(t-j) \quad (\text{B.2.7})$$

where $Q(t)$ is the cooling/heating load at time (t) and $q(t-j)$ is the heat gain/heat loss at time $(t-j)$. The $r(j)$ terms are response factors, which for a unit input excitation represent the actual cooling/heating load values:

The above equation can be re-written considering a finite number of terms as:

$$Q(t) = r(0)q(t) + r(1)q(t-1) + r(2)q(t-2) + \dots r(k)q(t-k) + r(k+1)q(t-k-1) + \dots r(k+n)q(t-k-n) \quad (\text{B.2.8})$$

Since the responses are typically decaying exponential in form, a relationship exists after k terms in which all succeeding $r(j)$ terms are linear and related through the common ratio:

$$C = \frac{r(k+1)}{r(k)}$$

where C is the common ratio.

Thus, equation (B.2.2) can be written as:

$$Q(t) = \sum_{j=0}^k r(j)q(t-j) + r(k) \sum_{j=k+1}^{\infty} C^j q(t-k-j) \quad (B.2.9)$$

A substantial reduction in solution time for this equation can be achieved by convolving the heating/cooling load, $Q(t)$, with past values. For example, if one substitutes, $(t=t-1)$ into equation (B.2.9) and performs the necessary algebraic operations, an equation of the following form results:

$$Q(t) = \sum_{j=0}^k r'(j)q(t-j) + C \cdot Q(t-1) \quad (B.2.10)$$

which relates the cooling/heating load at time t , $Q(t)$, to past values of the heat gain, $q(t-j)$, and the previous values of cooling/heating load, $Q(t-1)$. The response factors, $r'(j)$, in this case would be:

$$r'(j) = r(j) - C \cdot r(j-1) \quad (B.2.11)$$

with

$$r'(0) = r(0) \quad (B.2.12)$$

The expression (B.2.10) is itself a time series which can be convolved in a similar manner such that:

$$Q(t) = \sum_{j=0}^k r''(j)q(t-j) + C \cdot Q(t-1) + C' \cdot Q(t-2) \quad (B.2.13)$$

where

$$r''(j) = r'(j) - C' \cdot r'(j-1)$$

in which C' is the common ratio of (B.2.10). Thus, in general, the convolution can be carried as far as desired, and:

$$Q(t) = \sum_{j=0}^k V(j)q(t-j) + \sum_{j=1}^{k-1} W(j)Q(t-j) \quad (\text{B.2.14})$$

where V and W are respectively the load response factors and common ratio after $(k-1)$ common ratios have been invoked.

(d) Z-Transform Method

The Laplace transform of a continuous function $F(t)$ is defined as:

$$F(s) = \int_0^{\infty} e^{-st} F(t) dt \quad (\text{B.2.15})$$

which relates the time domain function, $F(t)$, to the complex plane domain function, $(F(s))$. The fact that a linear differential equation in $F(t)$ when transformed to the S -domain results

in an algebraic expression, the solution of which is much more straightforward, is an important attribute of the Laplace transform concept.

If a continuous function, $F(t)$, is sampled at regular intervals of time, $m\Delta$, one can relate the sampled output, $F_0(t)$, to the input, $F(t)$, through what is defined as a "sampling function"², $P(t)$. Mathematical simplification results if the sampling function is a series of unit impulses expressed as:

$$P(t) = \sum_{m=0}^{\infty} \delta(t-m\Delta) \quad (\text{B.2.16})$$

The sampled output is then:

$$F_0(t) = \sum_{m=0}^{\infty} F(m\Delta) \delta(t-m\Delta) \quad (\text{B.2.17})$$

² Reference 11, page 353.

The Laplace transform of equation (B.2.17) is:

$$F0(s) = \sum_{m=0}^{\infty} F(m\Delta)e^{-(m\Delta)s} \quad (\text{B.2.18})$$

A much simpler method for discrete time series analysis is obtained by letting $Z = e^{s\Delta}$, where Z is defined as the Z-transform of function $F(t)$.

$$F0(Z) = \sum_{m=0}^{\infty} F(m\Delta)Z^{-m} \quad (\text{B.2.19})$$

Note that, in this case, the output is strictly dependent only on the input values sampled at regular time intervals. Using this Z-transform definition, equation (B.2.6) can be written as:

$$Q(Z) = r(Z)q(Z) \quad (\text{B.2.20})$$

The convolution in the time domain of function $Q(t)$ is achieved in the Z-domain by multiplication and division of equation (B.2.20) by the expression $(1-C \cdot Z^{-1})$, where C is the common ratio of the $r(Z)$ series as defined previously, thus:

$$Q(Z)(1-C \cdot Z^{-1}) = r(Z)(1-C \cdot Z^{-1})q(Z) \quad (\text{B.2.21})$$

which when transformed yields equation (B.2.10). Successive applications of the same process leads to equation (B.2.14).

3. THERMAL NETWORK ANALYSIS

The thermal network method uses regions of uniform temperature within a structure to define the heat transfer processes which occur. Each region is defined by a characteristic node which may contain a heat capacity and/or may be a source of heat. Heat transfer between nodes is defined by a thermal conductance quantity. By performing a heat balance at each node a series of n-node equations are obtained which when solved simultaneously yield node solution temperatures. The following development, which lists the algorithms used in the thermal network technique, is detailed in Reference 10.

The heat balance equation of any node i would be

$$\sum_{j=1}^N K_{i,j}(t)[T_i(t) - T_j(t)] + M_i(t)(dT/dt)_i = S_i(t) + B_i(t)T_i(t) \quad (B.3.1)$$

where

$K_{i,j}(t)$ = thermal conductance between nodes i and j at time t

$T_i(t)$ = temperature at node i at time t

$T_j(t)$ = temperature at node j at time t

$M_i(t)$ = heat capacitance at node i at time t

$S_i(t), B_i(t)$ = constants which define the heat source capacity of node i at time t

N = number of nodes defining the system

The solution to this equation results in a form similar to the thermal balance solution scheme, i.e.

$$[C] [T] = [B]$$

where

$$\begin{aligned} C_{i,i} &= \frac{M_i(t)}{\Delta t} + -f\left(\sum_{j=1}^N K_{i,j}(t) - B_i(t)\right) \\ C_{i,j} &= -f K_{i,j}(t) \end{aligned}$$

and

$$\begin{aligned}
 B_i &= M_i(t)T_i(t=0) + f \left[S_i(t) + \sum_{j=1}^{NF} K_{i,j}(t) T_j(t) \right] \\
 &+ (1 - f) \left[\frac{M_i(t)}{M_i(t=0)} \right] \left[S_i(t=0) + B_i(t=0) T_i(t=0) \right. \\
 &\left. + \sum_{j=1}^N K_{i,j}(t=0) (T_j(t=0) - T_i(t=0)) \right] \quad (B.3.2)
 \end{aligned}$$

where f is a constant used to define the linear function solution to equation (B.3.1) and NF is the number of fixed temperature nodes. The above matrix is sized of course by the number of variable temperature nodes. Since this report will concentrate on the thermal balance and weighting factor techniques, additional information regarding the thermal network method should be obtained from Reference 10.

C. ANALYTICAL DEVELOPMENT OF ROOM SPECIFIC WEIGHTING FACTORS

The weighting factor concept discussed in Section B.2. stems from the work of Stephenson and Mitalas of the National Research Council of Canada, References 1 and 2. As stated in Appendix H.2, the presently published values of weighting factors were generated using a thermal balance solution for surface temperatures from which the zone load response was determined. A single space building with one externally exposed wall with a window was used as the typical structure and perturbations were made in the wall construction to determine the appropriate heavyweight to lightweight variation in resulted weighting factors. As a result of this approach, the published weighting factors are approximate for any arbitrarily defined space.

One of the primary tasks within the scope of analysis of this study entailed the investigation of generating room specific weighting factors. By producing an economical accurate means of so doing would obviously increase the capability of the weighting factor method in determining zone load and temperature fluxuations for any arbitrary structure.

The formulation described below is a technique developed by Z. Cumali and associates of Consultants Computation Bureau. A recursion relationship was developed such that weighting factors were generated for both radiation and room air temperature pulses. Additional work is presently in progress to also define conduction type weighting factors. The general procedure involves a thermal balance solution at time, $t=0$, for a unit pulse excitation input; after which all subsequent zone loads are determined using past values.

The surface temperature heat balance equation, (B.1.9), can be re-written as follows:

$$A_i \left[X_i(0) + h_i + \sum_{m=1}^{NS} G_{i,m} \right] T_i(t) - A_i \sum_{m=1}^{NS} G_{i,m} T_m(t) = - A_i \sum_{j=1}^t X_i(j) T_i(t-j) + q_{R_i}(t) + h_i A_i T_R \quad (C.1)$$

where the outside surface temperatures, $T_i^0(t)$, are assumed zero and the summation quantity on the right hand side deals with all past values of inside surface temperatures, $T_i(t)$, thus eliminating the use of past values of heat gain. In matrix form, equation (C.1) is written as:

$$\begin{bmatrix} C_{1,1} & C_{1,2} & \dots & C_{1,NS} \\ C_{2,1} & & & C_{2,NS} \\ \cdot & & \cdot & \\ \cdot & & \cdot & \\ \cdot & & \cdot & \\ C_{NS,1} & & C_{NS,NS} & \end{bmatrix} \begin{bmatrix} T_1(t) \\ T_2(t) \\ \cdot \\ \cdot \\ \cdot \\ T_{NS}(t) \end{bmatrix} = \begin{bmatrix} A_1 h_1 T_R + q_{R_1}(t) - \phi_1(t) \\ \cdot \\ \cdot \\ \cdot \\ \cdot \\ A_{NS} h_{NS} T_R + q_{R_{NS}}(t) - \phi_{NS}(t) \end{bmatrix} \quad (C.2)$$

or

$$[C] \cdot [T] = [B]$$

where

$$C_{i,i} = A_i \left[X_i(0) + h_i + \sum_{m=1}^{NS} G_{i,m} \right]$$

$$C_{i,m} = - A_i G_{i,m} = C_{m,i} = - A_m G_{m,i}$$

and

$$B_i = A_i h_i T_R + q_{R_i}(t) - \phi_i(t)$$

with

$$\phi_i(t) = A_i \sum_{j=1}^t X_i(j) T_i(t-j) \quad (C.3)$$

Each of the terms in the $[C]$ matrix are constant and independent of the solution temperatures, T_i . The B_i equation contains the excitation function which for a unit radiation impulse is described as follows:

$$\sum_{i=1}^{NS} q_{R_i}(0) = 1 \quad \text{and} \quad q_{R_i}(t) = 0 \quad \text{at} \quad t \geq 1$$

In this case, the room air temperature, T_R , equals zero, or a value equal to the outside air temperature. For a unit room air temperature pulse,

$$\begin{aligned} T_R &= 1 & \text{at} \quad t &= 0 \\ T_R &= 0 & \text{at} \quad t &\geq 1 \end{aligned}$$

The solution of equation (C.2) is obtained by inverting the $[C]$ matrix, thus

$$[T] = [C]^{-1} \cdot [B] = [K] \cdot [B] \quad (C.4)$$

For $j = t$, the solution temperatures can be written as:

$$T_i(t-j) = T_i(0) = \sum_{n=1}^{NS} K_{i,n} B_n(0) \quad (C.5)$$

where

$$B_n(0) = A_n h_n T_R + q_{R_n}(0)$$

and

$$\Phi_n(0) = 0$$

For $j < t$

$$T_i(t-j) = - \sum_{n=1}^{NS} K_{i,n} \Phi_n(t-j) \quad (C.6)$$

since for all times other than $t=0$ both the radiation heat gain and room air temperature are zero for a pulse input.

Substitution of equations (C.5) and (C.6) into equation (C.3) yields:

$$\begin{aligned}\phi_i(t) = & - A_i \sum_{j=1}^{t-1} X_i(j) \sum_{n=1}^{NS} K_{i,n} \phi_n(t-j) \\ & + A_i X_i(t) \sum_{n=1}^{NS} K_{i,n} B_n(0)\end{aligned}\quad (C.7)$$

Weighting factors are determined by obtaining the heating/cooling load response to the aforementioned impulse input heat gains. Specifically,

$$Q(t) = \sum_{m=1}^{NS} A_m h_m \left[T_R - T_m(t) \right] \quad (C.8)$$

A recursion relationship can be developed by considering the cooling load contribution from each surface, thus for $t \geq 1$:

$$Q_m(t) = A_m h_m \sum_{i=1}^{NS} K_{m,i} \phi_i(t) \quad (C.9)$$

Substitution of equation (C.7) into the expression yields after further reduction:

$$\begin{aligned}Q_m(t) = & - A_m h_m \sum_{i=1}^{NS} K_{m,i} \sum_{j=1}^{t-1} \frac{X_i(j)}{h_i} Q_i(t-j) \\ & + A_m h_m \sum_{i=1}^{NS} K_{m,i} A_i X_i(t) \sum_{n=1}^{NS} K_{i,n} B_n(0)\end{aligned}\quad (C.10)$$

and the total load is:

$$Q(t) = \sum_{m=1}^{NS} Q_m(t) \quad (C.11)$$

Therefore, for all times after $t=0$, the resultant load can be determined by considering past values of the load. Knowing the load response enables one to calculate the weighting factors by application of the techniques described in Section B.2.

D. LASL TEST CELL RESULTS

Figure D.1 presents a description of the LASL test cell modeled for the comparison of the thermal loads calculated by BLAST and DOE-1.

Surface layer descriptions are listed from outside surface and the model represents a configuration defined by LBL for its own testing purposes. To simplify the analysis, an overhang attached to surface 1 was deleted from the structure. The test cell is constructed of three external walls (north, south, and west facing), an internal wall (east facing-no heat transfer), an exposed floor and sloping roof. Within the south facing wall is a double-pane plexiglas window covering approximately 73% of the wall area. Each of the north, east, and west walls are constructed of a lower section using concrete and insulation and an upper section which is primarily insulation.

1. CONSTANT ROOM AIR TEMPERATURE

Initially, both the DOE-1 weighting factor program and BLAST thermal balance program were run at constant room air temperature using a similar seven day weather profile for Los Alamos, New Mexico. Figure D.2 presents a comparison for three days of the daily loads calculated by BLAST and DOE-1 using the pretabulated weighting factors intrinsic to the program. In addition, Figure D.2 shows the range of loads calculated in DOE-1 using both the lightweight and heavyweight weighting factors. The test cell itself is of heavy weight construction and thus the 130 lb/ft DOE-1 results should be compared with BLAST.

As can be seen, the DOE-1 loads are consistently lower than BLAST throughout the first fourteen hours of each day; however, the daily trend is somewhat similar, although with an apparent time shift. To determine the source of this difference, one must consider the algorithms each program uses in defining the loads. DOE-1 generates component loads, both weighted and unweighted, such as transmitted

solar radiation, conduction heat gain through walls, windows, etc. BLAST, on the other hand, does not separate the load components. In BLAST, surface temperature are calculated explicitly from which the total zone load is obtained.

The time shift mentioned above can be accounted for by considering Figure D.3 which presents the solar radiation transmitted into the zone for both DOE-1 and BLAST with the DOE-1 values shifted 1/2 hour to the left. The DOE-1 values are actually a summation of the solar radiation transmitted into the space and solar radiation absorbed by the window. This is done because the glass conduction load in DOE-1 is calculated by relating the temperature difference between the outside air and zone space air, thus the absorptivity of the glass is handled in the radiation terms and not the conduction quantities. Revisions were next applied to DOE-1 in the manner described in Appendix H.3 of this report. This technique calculates an average surface temperature for each surface and separates the convective and radiative heat gain components due to conduction. The convective portion of surface heat gain contributes immediately to the zone load, whereas the radiative portion affects the other surfaces. An approach such as this negates the use of conduction type weighting factors which at this time was deemed necessary because of the unresolved status of their meaning. In addition, room specific weighting factors were generated for the test cell using the method outlined in Section C. A unit pulse in which 80% was assigned to the floor generated the load response and resultant weighting factors as shown on Figure D.4. Also presented is the corresponding response generated by the BLAST program; a procedure which is described in Appendix H.1.

Figure D.5 compares the DOE-1 results using the above revisions with the BLAST total load. As can be seen a satisfactory match is obtained. The only apparent discrepancy arises in day 3 and this is no doubt due in part to the different solar routines within each program, specifically the cloud cover portion.

2. VARIABLE ROOM AIR TEMPERATURE

The weighting factor technique is also used by DOE-1 to determine room air temperature fluxuations. The method, which is described in Section B.2 uses the constant room air temperature loads in conjunction with weighting factors generated by a room air temperature pulse to define actual variations in temperature. Room conductance values, infiltration and ventilatilon system quantities are handled as correction terms to the defined weighting factors which also must be applied to the constant temperature generated loads.

Initially, a comparison was made of the thermal balance generated and weighting factor generated room air temperature results. Both infiltration and system air inputs were set to zero and the DOE-1 constant temperature loads were set equal to the BLAST constant loads. This procedure enabled a more direct comparison since the subtle differences in constant air temperature were eliminated and thus the perturbations due to the algorithmic variations were eliminated. Also, a degree of confidence was established in the room air temperature weighting factors by the procedure outlined in Section C. This was particularly important since the magnitude of the BLAST generated weighting factors seemed unrealistic.

Figure D.6 presents the zone load response to a unit air temperature pulse using the method described in Section C. Also presented are the resultant weighting factors calculated and used for the results shown on Figure D.7. As can be seen, the DOE-1 generated air temperatures vary from approximately 5° below the BLAST values for day one to 2° for day three. This fact can be attributed to the fact that the DOE-1 weighting factor method employs a constant conductance correction term. Closer agreement would result if the conductance was time varying and dependent on inside and outside temperatures. In addition, although a six day constant weather initialization period was used in both programs, the DOE-1 results reached a steady state quicker than the

BLAST results. Figure D.8 shows the same thermal balance air temperature values as Figure D.7; however the weighting factor results presented were obtained using the constant air temperature loads generated by DOE-1, (Figure D.5). The effect of input loads value changes is immediately observable, although the relative difference between Figures D.7 and D.8 is not significant.

3. TEST CELL DATA

Thus far in this report, the weighting factor and thermal balance methods of determining zone loads and air temperatures have been discussed and compared. It has been shown that both techniques are viable means of obtaining similar results. Inherent in each are an assortment of algorithms necessary for the calculation of the various parameters required for solutions. One should expect resultant magnitude differences. The verification of any computational quantity usually rests on a comparison with measured test data.

The thermal balance approach has been somewhat verified by work accomplished at LBL using LASL test cell air temperature data. The same seven day weather profile discussed previously generated measured inside zone air temperatures which were used as a base for substantiation of computer simulation results. Figure D.9 presents a comparison of the measured room air temperature for day 1 with the DOE-1 calculated values. The infiltration of outside air in DOE-1 was varied since this quantity was not available from measured data. Using an air change value of 2-1/2 in the simulation yielded a quite satisfactory correlation with the test results. This same level of infiltration was next applied for the seven test weather days, the results of which are shown on Figure D.10. Whatever differences are apparent can be attributed to several items; but primarily, varying infiltration and conductance, and solar input quantities. DOE-1 uses a predefined cloud cover

modifier to split the incident solar radiation into direct and diffuse quantities. A more reasonable approach, and DOE-1 has the facility, would be to convert the actually measured solar data. Further studies are needed in each of the above areas.

It should be noted that for day six on Figure D.10, the minimum value of cloud cover modifier used in DOE-1 yielded solar quantities which did not agree with the measured values; thus, a revision was made to the program to reflect the proper amount of solar input.

FIGURE D.1 - LASL TEST CELL

SURFACE	MATERIAL	THICKNESS (ft)	DENSITY (lb/ft ³)	SPECIFIC HEAT (Btu/lb·°F)	CONDUCTIVITY (Btu-in)/(hr·ft ² ·°F)
1	Plywood	.0521	34	.29	.0667
	Douglas Fir	.292	32	.33	.0667
	Styrofoam	.083	1.8	.29	.0208
2	Plywood	.0521	34	.29	.0667
	Stud Ins	.292	5.01	.216	.0316
	Styrofoam	.083	1.8	.29	.0208
	Concrete	.458	130	.20	.7576
3	Plywood	.0521	34	.29	.0667
	Stud Ins	.292	5.01	.216	.0316
	Styrofoam	.083	1.8	.29	.0208
4	Styrofoam	.083	1.8	.29	.0208
	Stud Ins	.292	5.01	.216	.0316
	Styrofoam	.083	1.8	.29	.0208
	Concrete	.458	130	.20	.7576
5	Styrofoam	.083	1.8	.29	.0208
	Stud Ins	.292	5.01	.216	.0316
	Styrofoam	.083	1.8	.29	.0208
6	Plywood	.0208	34	.29	.0667
	Stud Ins	.458	5.75	.216	.0266
	Plywood	.0625	34	.29	.0667
	Concrete	.458	130	.20	.7576
7	Ply-Tar	.0521	34	.29	.0667
	Stud-Air	.292	4.07	.251	.26
	Airspace	Resistance = .93			
	Stud Ins Db1	.458	5.75	.216	.0266
	Corr Steel	.005	489	.12	26.2
8	Plexiglass	Resistance = .023			
	Airspace	Resistance = .93			
	Plexiglass	Resistance = .023			

FIGURE D.2 - LASL TEST CELL TOTAL LOAD COMPARISON AT CONSTANT CELL
TEMPERATURE USING PRETABULATED WEIGHTING FACTORS

DAY 1

DAY 2

DAY 3

FIGURE D.3 - LASL TEST CELL TRANSMITTED SOLAR RADIATION
COMPARISON BETWEEN BLAST AND DOE-1

DAY 1

DAY 2

DAY 3

FIGURE D.4 - LASL TEST CELL RESPONSE TO UNIT RADIATION PULSE
INPUT - WEIGHTING FACTOR GENERATION

FIGURE D.5 - LASL TEST CELL TOTAL LOAD COMPARISON AT CONSTANT CELL
TEMPERATURE USING REVISED CONDUCTION/CONVECTION EQUATIONS
AND CELL SPECIFIC RADIATION WEIGHTING FACTORS

FIGURE D.6 - LASL TEST CELL RESPONSE TO UNIT ROOM AIR
TEMPERATURE PULSE INPUT - WEIGHTING FACTOR GENERATION

FIGURE D.7 - LASL TEST CELL ROOM AIR TEMPERATURE COMPARISON
USING THERMAL BALANCE CONSTANT TEMPERATURE LOADS
AND CELL SPECIFIC TEMPERATURE WEIGHTING FACTORS

DAY 1

DAY 2

DAY 3

FIGURE D.8 - LASL TEST CELL ROOM AIR TEMPERATURE COMPARISON
USING WEIGHTING FACTOR CONSTANT TEMPERATURE LOADS
AND CELL SPECIFIC TEMPERATURE WEIGHTING FACTORS

DAY 1

DAY 2

DAY 3

FIGURE D.9 - LASL TEST CELL TEMPERATURE DATA COMPARISON WITH
CALCULATION RESULTS USING REVISED CONDUCTION/
CONVECTION EQUATIONS AND CELL SPECIFIC WEIGHTING
FACTORS IN DOE-1, DAY 1

FIGURE D.10 - LASL TEST CELL TEMPERATURE DATA COMPARISON WITH
CALCULATED RESULTS USING REVISED CONDUCTION/
CONVECTION EQUATIONS AND CELL SPECIFIC WEIGHTING
FACTORS IN DOE-1

E. SUMMARY

This report has been written as a first step in consolidating thermal load calculation methods for possible use in passive solar design structures. Initially, a brief discussion of three calculation techniques was presented: thermal balance, weighting factor and thermal network. The algorithms annotated within the report (Section B) reflect the general structure of each of the techniques without regard to particular computer simulation programs presently in use. However, within the Appendix are contained specific comments on three programs used to perform the subsequent analysis in Sections C and D. This study has concentrated on the weighting factor and thermal balance approaches to zone load determination. The computer programs utilized (DOE-1 and BLAST), in addition to using different solution techniques, also contain varying algorithms for parameters required as input quantities to the general solution equations. The Appendix has attempted to reflect certain of these program peculiar aspects in a cursory fashion since this task was not within the scope of work of the contract. The Appendix also contains a discussion on the NRC BR202 program which is a thermal balance scheme used to generate the weighting factors presently in DOE-1. The rather specific nature of the BR202 program resulted in a concentrated effort to generate room specific weighting factors, the formulation of which is presented in Section C. With the successful development of a simple recursion relationship, appropriate weighting factors can now be obtained for any arbitrarily defined space. A degree of confidence in both the weighting factor and thermal balance approaches was obtained by the analysis presented in Section D which compares actual test data with simulation results.

F. FUTURE DEVELOPMENTS

This report has discussed the work accomplished to date under DOE contract number EM-78-C-01-5221, Passive Solar Calculation Methods. It represents a consolidation of the effort during the period of October 15, 1978 through March 15, 1979. This section details what specific tasks still remain to be completed.

1. SENSITIVITY ANALYSIS

The development of the low computer cost recursion technique for generating room specific weighting factors (SECTION C) will enable a comprehensive sensitivity study of parameters affecting zone load and room air temperature fluxuations. Of partitcular importance are the influence of inside convection coefficients and response factor terms which directly effect the magnitude of resultant weighting factors. Initial studies indicate that both floor and ceiling values of convection coefficients, which vary with direction of heat flow, definitely influence, to a large degree, the resultant load and air temperature responses to unit pulse inputs. Additional analysis will be performed on a variety of space/building structures to determine the influence of size, external wall configuration, window construction and location, etc. Specific corrections to handle time varying conductance values will also be investigated.

2. MULTIZONE ANALYSIS

The current public domain computer program which uses the thermal balance approach to zone load calculations is BLAST (Appendix H.1). BLAST has no provisions for handling heat transfer between zones within a particular building structure. In addition, the algorithms in BLAST

which are used to define the various quantities necessary for solution are somewhat different than the corresponding algorithms utilized in the weighting factor simulation program, DOE-1 (Appendix H.3). To enable a more feasible comparison between the weighting factor and thermal balance approaches to load determination, and also to investigate the effect of multizone thermal analysis, a CCB designed thermal balance scheme will be put into operation. The initial work on this program was begun several years ago and at present the version is in the checkout phase. This program will accept direct parameter inputs and, as such, will enable a more accurate and valid comparison with the weighting factor method.

The multizone capability will enable the successful completion of Task 5 of the Statement of Work (Appendix H.4) which entails the investigation of room to room coupling of both conduction and convection quantities.

3. PASSIVE SOLAR ELEMENT ANALYSIS

This portion of the analysis is detailed in Task 4 of the Statement of Work (Appendix H.4). At present, neither the weighting factor nor thermal balance schemes have the capability for analyzing specific passive solar elements and their influence on load quantities. An attempt will be made to collect what information is available on the subject and determine methods for incorporation into each of the thermal load calculation methods. Close coordination with LBL will be maintained since they are presently developing passive solar element algorithms.

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APPENDIX 1 -- BLAST SPECIFIC DISCUSSION

The Building Loads Analysis and System Thermodynamic Program (BLAST) is a "...computer program for estimating (1) hourly space heating and cooling requirements, (2) hourly performance of fan systems, and (3) hourly performance of conventional heating and cooling plants, total energy plants, and/or solar energy systems..."³ The general structure of the BLAST program consists of a language processor, a loads calculation program, an air handling system simulation program, and a central energy plant simulation program. This discussion will treat only those portions of BLAST which deal with thermal load analysis.

BLAST uses the thermal balance technique discussed in Section B.1 of this report to calculate the heating/cooling loads of a space. A heat balance is performed on each surface within the space from which surface and room temperatures are determined. The zone load in BLAST is calculated in a somewhat different, although equivalent, manner than described in Section B.1, (see discussion below).

The BLAST load calculation sequence is given on Figure H.1.1. The program loop structure is such that each zone is treated independent of other zones within a building, and thus heat transfer among zones is not calculated. This series type of structure hampers implementation of revisions for multizone analysis.

Three primary loop structures are apparent in BLAST. A zone loop which controls the simulation of each zone, a load initialization loop which performs a 6-day simulation using a constant weather day to stabilize transients, and a run period loop that performs hourly load calculations over the time period specified at input.

³ Reference 4.

(a) Special BLAST Concepts

In addition to the basic thermal balance discussion in Section B.1, the following concepts are employed in BLAST:

(1) A distinction between solar absorptance, thermal absorptance and lighting absorptance is made in BLAST for each surface exposed to the zone space air. The radiation component of heat gain from transmitted solar, equipment, occupants, and lights (equation B.1 in Section B.1), therefore, has an additional functional dependence on surface absorptance. For example, given the thermal absorptivity for each surface, α_{t_i} , the fraction of internally generated thermal radiation, α_{tf_i} , absorbed by a surface is defined as:

$$\alpha_{tf_i} = \frac{\alpha_{t_i} A_i}{NS \sum_{m=1} \alpha_{t_m} A_m} \quad (H.1.1)$$

Thus, the (f_e) term in equation (B.1.7) would be multiplied by α_{tf_i} for each surface. The same is true for the other f 's, using the appropriate type absorptivity.

(2) The inside surface heat transfer coefficients, h_i , used in BLAST are variable. A check is made each hour to compare the surface temperatures with the room temperature to establish the heat flow direction from which the h_i values are set. This is important only for surfaces which are horizontal in orientation.

(3) The radiation view factors, $F_{i,m}$, are calculated in BLAST by an approximate method using the expression:

$$F_{i,m} = \frac{A_m}{\sum_m A_m} \quad (H.1.2)$$

where A_m is the surface area of surface m .

(4) The zone load calculation scheme in BLAST uses a linear expression relating the heating and cooling capacity of the system controlling the space to the room temperature. Both a room temperature dependent coefficient and independent coefficient are calculated at each hour. An expression of the following form is used:

$$Q_t = q_{sd_t} T_R(t) + q_{si_t} \quad (H.1.3)$$

where

- Q_t = zone load
- q_{sd_t} = temperature dependent factor
- q_{si_t} = temperature independent factor
- $T_R(t)$ = room air temperature at time t

The terms q_{sd_t} and q_{si_t} relate the current zone temperature schedule to the throttling range of the system. Consider the diagram below which represents the heating/cooling space temperature control:

The zone load is defined as "...the heat picked up by the room air (or that lost by the room air) which has to be removed (or added) by the central air conditioning system...".⁴ For any room temperature outside the dead band and within the maximum capacity of the system a linear relationship exists between the temperature and zone load. The temperature dependent factor, q_{sd_t} , is simply the slope in the above diagram, for example, a cooling load yields:

⁴ Reference 5, page 111.

$$q_{sd_t} = \frac{COOLmax}{(T_4 - T_5)} \quad (H.1.4)$$

and

$$q_{si_t} = - q_{sd_t} T_4 \quad (H.1.5)$$

Thus

$$Q_t = \frac{COOLmax}{(T_4 - T_5)} (T_R(t) - T_4) \quad (H.1.6)$$

(b) Pulse Generating Revisions to BLAST

In addition to being used as a thermal load calculation program, revisions were incorporated into BLAST to enable the generation of room weighting factors. The BR202 program, discussed in Appendix 2, was used in the past by the National Research Council of Canada for such purposes; however, BR202 is rather limited in that it was specifically designed to analyze a predefined space. BLAST, with its ability to accept any space definition, is therefore, with minor changes, capable of producing space specific weighting factors.

The weighting factor concept, discussed in Section B.2 of this report, states that for a unit input of heat gain, the resultant load response can be used to determine room weighting factors. The heat gain components arise from radiation, convective, conduction and room air temperature. Heat gain by convection is instantaneous, thus its contribution to the zone load is not delayed and the resultant weighting factor for a unit pulse input is 1.0. The other three components of heat gain are delayed which implies that a time response analysis is necessary to define the weighting factors.

At the present time, there is some confusion regarding the meaning of conduction weighting factors; therefore, the revisions to BLAST deal with heat gain by radiation and room air temperature.

(1) Radiation Weighting Factors

The general matrix equation for surface temperature calculations using the thermal balance method is (see Section B.1):

$$\begin{bmatrix} C_{1,1} & C_{1,2} & \cdots & C_{1,NS+1} \\ C_{2,1} & C_{2,2} & \cdots & C_{2,NS+1} \\ \cdot & & & \\ \cdot & & & \\ \cdot & & & \\ C_{NS+1,1} & \cdots & \cdots & C_{NS+1,NS+1} \end{bmatrix} \cdot \begin{bmatrix} T_1^I(t) \\ T_2^I(t) \\ \cdot \\ \cdot \\ \cdot \\ T_R(t) \end{bmatrix} = \begin{bmatrix} B_1 \\ B_2 \\ \cdot \\ \cdot \\ \cdot \\ B_{NS+1} \end{bmatrix} \quad (H.1.7)$$

The right hand side of this expression contains the radiation components of heat gain; thus, the "B" terms in BLAST were revised such that the only radiation input came from the unit excitation. Since radiative effects come from different sources, i.e., solar equipment, lights, and occupants, a distribution term was also defined to distribute the excitation among the various room surfaces in a manner consistent with the source type. A throttling range for the system was defined to hold the room air temperature fixed.

(2) Room Air Temperature Weighting Factors

To satisfactorily generate a room air temperature pulse, the (NS+1) matrix above was reduced by the room air equation and the room air temperature itself was made part of the "B" terms. This was consistent with the thermal balance development for constant room air temperature (Section B.1.) and simplified the revision process to BLAST. Thus:

$$B_i' = B_i + A_i h_i T_R \quad (H.1.8)$$

The weighting factors themselves were generated by incorporating additional routines into the BLAST structure to perform the convolution operations discussion in section B.2.

FIGURE H.1.1 - BLAST LOADS CALCULATION FLOW

APPENDIX 2 -- BR202 SPECIFIC DISCUSSION

The BR202 computer program was developed by the National Research Council of Canada for the purpose of generating room weighting factors for use in loads calculations. The published weighting factors in References 5 and 6 come from this work. Techniques detailed in References 1 and 2 were used to determine two groups of weighting factors; the first of which are surface temperature response factors, obtained by the response to a unit excitation at each surface within a pre-defined space; and, a second set of cooling load response factors obtained by combining various sets from the cooling load response consolidation of the first group. The aforementioned published ASHRAE weighting factors represent a third group which combines sets from the second group to obtain "...one set of factors for each component of heat gain ..."⁵

BR202 uses a thermal balance scheme similar to that discussed in Section B.1; however, the heat gain components arise from unit excitations and not from specific forms of energy transmitting quantities such as solar, equipment, occupants, etc.

Figure H.2.1 presents a description of the space used by the BR202 program. It consisted of one south facing external wall composed of concrete with a window covering approximately 41% of the wall area; a north facing wall constructed of brick adjacent to a corridor; and two east and west facing partitions. A plenum air space was defined above an acoustic tile ceiling. Both the floor construction and ceiling construction above the air space were primarily concrete. The room itself was assumed to be surrounded on all sides by similar spaces with exception of the south facing wall. The specific material properties are listed on Table H.2.1. Also listed on Figure H.2.1 are the twenty-six specific surfaces which were defined for the purpose of accepting a unit excitation in heat flux and the nine surfaces and air spaces which received a unit temperature excitation.

⁵ Reference 5, page 179.

Since the BR202 program was designed specifically to analyze this one particular space, there was no need to develop a language processor as in the BLAST and DOE-1 programs. Data was input through the normal FORTRAN programming techniques. In addition, the only looping structure within the program related to the algebraic operations necessary for the algorithm solutions.

Table H.2.2 lists the second group of factors generated by the program; the previously mentioned cooling load response factors. This second set "... combines all of the sets in group one that pertain to diffuse solar radiation into a single set; it combines all of the sets for direct solar radiation incident on the room surfaces other than the various window surfaces, floor, and furniture into another combined set; and lastly, it combines all the sets that pertain to excitation by the power supplied to the lights into a single set..."⁶

As stated previously, the BR202 program was structured to generate a thermal balance solution to inside surface temperatures. A unit flux pulse applied individually to each surface yielded response factors which were summed for all the surfaces to yield the cooling load. A somewhat different approach was used in this report to generate the response to a unit pulse. The pulse itself was distributed to each surface and the resultant thermal balance matrix solve at each time increment. Figure H.2.2 presents a comparison of the BR202 results with a BLAST program generated response (see procedure in Appendix H.1). Both a distributed pulse response and one in which 80% was given to the floor were obtained from BLAST. The BR202 data represents a composite response of direct solar radiation quantities. Specific reasons for the differences are as follows: the composite calculated by BR202 may not represent the same radiation distribution given in BLAST calculations; BR202 calculates view factors in an exact manner using the method described in Section B.1, whereas BLAST uses an approximate form; finally, both input quantities for defining the space and other algorithmic differences are no doubt prevalent, a fact which was difficult to isolate because of the lack of documentation for both programs.

⁶ Reference 5, page 179.

FIGURE H.2.1 - BR202 BUILDING DESCRIPTION

FLUX EXCITATION

- 1 FLOOR UPPER FRONT
- 2 FLOOR UPPER BACK
- 3 CEILING LOWER BACK
- 4 CEILING LOWER FRONT
- 5 EAST PARTITION BACK
- 6 EAST PARTITION FRONT
- 7 WEST PARTITION BACK
- 8 WEST PARTITION FRONT
- 9 CORRIDOR INSIDE
- 10 WINDOW INSIDE
- 11 OUT-WALL BELOW WINDOW
- 12 OUT-WALL ABOVE WINDOW
- 13 EAST OUTSIDE WALL
- 14 WEST OUTSIDE WALL
- 15 FURNITURE
- 16 INSIDE GLASS
- 17 INTERPANE BLIND
- 18 OUTSIDE GLASS
- 19 CEILING UPPER FRONT
- 20 CEILING UPPER BACK
- 21 CEILING SPACE AIR-FRONT
- 22 CEILING SPACE AIR-BACK
- 23 FLOOR LOWER FRONT
- 24 FLOOR LOWER BACK
- 25 OUT-WALL CEILING SPACE
- 26 OUT-WALL CORRIDOR SPACE

TEMPERATURE EXCITATION

- 26 CORRIDOR WALL
- 11 OUT-WALL BELOW WINDOW
- 12 OUT-WALL ABOVE WINDOW
- 13 EAST OUTSIDE WALL
- 14 WEST OUTSIDE WALL
- 25 SOL-AIR OUTSIDE
- CORRIDOR SPACE OUTSIDE
- 18 SOL-AIR GLASS
- ROOM AIR

TABLE H.2.1 - BR202 BUILDING MATERIAL PROPERTIES

<u>SURFACE</u>	<u>MATERIAL</u>	<u>THICKNESS</u> <u>(ft)</u>	<u>DENSITY</u> <u>(lb/ft³)</u>	<u>SPECIFIC HEAT</u> <u>(Btu/lb·°F)</u>	<u>CONDUCTIVITY</u> <u>(Btu·in)/(hr·ft²·°F)</u>
SOUTH WALL	Out Film Res	Resistance = .25			
	Concrete	.5	140	.156	.75
	Insulation	.0833	20	.25	.35
NORTH WALL	Out Film Res	Resistance = .715			
	Plaster	.0417	100	.2	.42
	Brick	.3333	70	.156	.44
	Plaster	.0417	100	.2	.42
EAST/WEST WALL	Partition	.1667	90	.2	.167
CEILING	Acoustic Tile	.0625	30	.2	.035
	Furniture	.1667	34	.6	.09
FLOOR	Concrete	.3333	140	.156	.75
	Tile	Resistance = .08			
WINDOW	Glass/Shade	Resistance = 2.12			

TABLE H.2.2 - BR202 PROGRAM WEIGHTING FACTOR GROUPING

DIFFUSE SOLAR RADIATION
SOLAR RADIATION ABSORBED BY INSIDE SHADE
SOLAR RADIATION ABSORBED BY INSIDE GLASS PANE
SOLAR RADIATION ABSORBED BY INTER PANE SHADE
DIRECT SOLAR RADIATION ABSORBED BY FURNITURE
DIRECT SOLAR RADIATION ABSORBED BY FLOOR SURFACE
DIRECT SOLAR RADIATION ABSORBED BY INSIDE ROOM
SURFACES OTHER THAN FLOOR AND FURNITURE
HEAT GAIN THROUGH WINDOW OTHER THAN TRANSMITTED
SOLAR RADIATION AND OUTSIDE WALL
LIGHT POWER INPUT
SOL-AIR TEMPERATURE - WINDOW
SOL-AIR TEMPERATURE - WALL
CORRIDOR AIR TEMPERATURE
ROOM AIR TEMPERATURE
ROOM COOLING PULSE

FIGURE H.2.2 - BR202 BUILDING RESPONSE TO A UNIT RADIATION
PULSE, COMPARISON OF BR202 AND BLAST

APPENDIX 3 -- DOE-1 SPECIFIC DISCUSSION

The DOE-1 computer program is a total energy analysis program. Calculation of building loads is performed in addition to simulations of air handling systems and central energy plants. Although designed somewhat differently than BLAST in its data file structure, the program contains four distinct parts, as does BLAST. A language processor interprets and translates the input data given by the user; a loads program performs thermal load calculation for each space within a building; the systems and plant portions simulate typical heating, ventilation and air conditioning pieces of equipment. This discussion will deal primarily with the loads portion of DOE-1; however, because room air temperature variations are treated in the systems part, certain aspects of systems will also be discussed.

DOE-1 uses the weighting factor technique discussed in Section B.2 of this report to calculate the heating/cooling loads of a space. Pretabulated weighting factors, published in Reference 5 , are used to relate radiative heat gain from solar, equipment, lights, and occupants and conductive heat gain through walls, roofs, floors, and windows to the total space load calculations. Room air temperature fluxuations are also handled by the use of weighting factors.

The DOE-1 load calculation sequence is given on Figure H.3.1. The loop structure is different than the BLAST structure in that the outermost loop controls the run period. The zone loop is located within the run period loop. For each zone, a three day initialization is performed using a constant weather day to stabilize transients. Load calculation for each zone are done in parallel rather than in a series fashion as in BLAST. Zone to zone heat transfer calculations are performed in DOE-1 upon specification of the appropriate command. Figure H.3.2 lists the current values of weighting factors present in DOE-1.

(a) Special DOE-1 Concepts

In this section are discussed specific DOE-1 relationships, which

affect the resultant thermal load and room air temperature values.

- (1) The total solar heat gain through glass is computed based on the sum of the transmitted solar radiation and absorbed solar radiation. This heat gain is subsequently weighted by the pretabulated solar radiation weighting factors to determine the zone load due to solar radiation.
- (2) The amount of direct normal and diffuse solar radiation is determined through the use of the cloud cover modification factor which is the ratio of the radiation on a horizontal surface with cloud cover to the ratio of the radiation for a clear sky. Predefined equations which are functions of solar altitude angle and cloud type are used to calculate the modification factor. The weather reading routine in DOE-1 does not, as yet, although storage facilities exist, have the capability of handling directly measured solar data. As stated in Section D of this report, the calculated cloud cover modification factors and thus the resultant solar intensity for one of the test weather days were too high when compared to the actual solar data. A correction was thus made to the program to accept the actual solar values.
- (3) The inside surface convection coefficient of each delayed surface is defined as a resistance layer of the wall and the resultant response factors reflect this effect. A simplification results in performing the heat balance of the outside surface (see Section B.2) since inside surface temperatures are therefore not computed. A portion of the discussion below discusses proposed revisions to DOE-1 which enable an average surface temperature to be computed. In this case the convection coefficients are dealt with separately after the definition of response factors.
- (4) The heat conductance gain through glass is defined by an equation such as:

$$q_G = U_G A_G (T_O - T_R) \quad (H.3.1)$$

where

U_a = glass conductance

A_a = glass area

T_o = outside dry bulb temperature

T_R = inside Zone air temperature

A heat balance of the outside surface is thus not performed as in the case of delayed and quick external walls. The proposed revision discussed below, however, does incorporate a temperature distribution through the glass surfaces. The previously mentioned solar radiation absorbed by the glass becomes part of the heat balance performed.

(5) The overall space conductance value used in the systems portion of DOE-1 to correct the normalized values of room air temperature weighting factors is calculated based on the wall conductances and glass resistance values. No provision is made for variable conductances due to temperature and wind effects. While this factor does not seem to be critical, future DOE-1 revisions should enable a time varying conductance quantity.

(b) Revisions to DOE-1

The investigation into the mechanics of the BR202 program resulted in some confusion regarding the definition of conduction weighting factors. Initial results of the comparison between the BLAST thermal balance and DOE-1 weighting factor load calculation schemes also indicated that perhaps the conduction portion of the DOE-1 equations warranted further analysis. Therefore, revisions were made to DOE-1 such that an average inside surface temperature for each surface within the space was calculated and the conduction component of the zone load was related to the convective component of heat gain directly without the use of weighting factors.

The revision employs the basic concept of heat balance of both inside and outside surfaces. In a manner similar to the development in Section B.1, the conduction heat gain can be expressed as:

$$q_{K_i}(t) = \left[\sum_{j=0}^{n_i} x_i(j) T_i^I(t-j) - \sum_{j=0}^{n_i} y_i(j) T_i^O(t-j) \right] A_i + c_i \cdot q_{K_i}(t-j) \quad (H.3.2)$$

This expression is equal to the convective and radiative heat gain:

$$q_{C_i}(t) + q_{R_i}(t) = h_{C_i} A_i \left[T_R - T_i^I(t) \right] + h_{R_i} \left[TA_i^I(t) - T_i^I(t) \right] A_i \quad (H.3.3)$$

where

h_{C_i} = convective heat transfer coefficient of surface i

h_{R_i} = radiative heat transfer coefficient of surface i

$TA_i^I(t)$ = the average temperature of surfaces seen by surface i at time t

The average temperature, $TA_i^I(t)$, can be approximated by:

$$TA_i^I(t) = \frac{\sum_{m=1}^{NS-1} A_m T_m^I(t-1)}{\sum_{m=1}^{NS} A_m} \quad (H.3.4)$$

where

NS = number of surfaces within the space

This equation reflects the influence of the other surface temperatures on surface i at time t.

The radiative heat transfer coefficient would therefore equal:

$$h_{R_i} = 4E_i \sigma \left[TA_i^I(t) \right]^3 \quad (H.3.5)$$

Performing a similar heat balance at the outside surface allows the simultaneous solution for inside surface temperature, $T_i^I(t)$, from which the conductive zone load is determined by:

$$Q_K(t) = h_{Ci} A_i [T_R - T_i^I(t)] \quad (H.3.6)$$

For surfaces which are not delayed such as glass and quick external walls a similar heat balance was performed and zone loads calculated in the same manner.

FIGURE H.3.1 - DOE-1 LOADS CALCULATION FLOW

TABLE H.3.2 - PRETABULATED WEIGHTING FACTORS IN DOE-1SOLAR RADIATION WEIGHTING FACTORS

	V_0	V_1	W_0	W_1
LIGHT WEIGHT	.224	-.044	1.0	-.82
MEDIUM WEIGHT	.197	-.067	1.0	-.87
HEAVY WEIGHT	.187	-.097	1.0	-.91

CONDUCTION WEIGHTING FACTORS

	V_0	V_1	W_0	W_1
LIGHT WEIGHT	.703	-.523	1.0	-.82
MEDIUM WEIGHT	.681	-.551	1.0	-.87
HEAVY WEIGHT	.676	-.586	1.0	-.91

ROOM AIR TEMPERATURE WEIGHTING FACTORS

	G_0	G_1	G_2	P_0	P_1
LIGHT WEIGHT	1.68	-1.73	0.05	1.0	-.82
MEDIUM WEIGHT	1.81	-1.89	0.08	1.0	-.87
HEAVY WEIGHT	1.85	-1.95	0.10	1.0	-.93

APPENDIX 4 -- STATEMENT OF WORK

The work is comprised of the following five tasks and their components:

TASK 1 - EVALUATION OF EXISTING ANALYSIS TECHNIQUES

- a. Identify the specific algorithms and techniques used for thermal load calculations in DOE-1.
- b. Identify the specific algorithms and techniques used for thermal load calculations in BLAST.

The purpose of sub tasks (a) and (b) is to establish the similarity and differences of the component load calculation methods in the two programs so that a basis may be established for comparison of results.

- c. Establish approximate degree of divergence of the weighting factor technique from the thermal balance technique. DOE-1 uses pretabulated weighting factors published by ASHRAE. The comparison of BLAST and DOE-1 results for a selected set of rooms with different constructions and parameters will be used to identify the degree of divergence. Thermally light rooms (negligible delay in heat transfer), medium, heavy and very heavy constructions will be used and some changes in surface and heat transfer parameters will be made.
- d. Identify the methods used for coupling thermally massive elements in the load calculation and system simulation parts of DOE-1 and BLAST programs.
- e. Coordinate work under this task with biweekly meetings of the LBL/LASL passive solar analysis group.

TASK 2 - BLAST/DOE-1 PROGRAM INTERFACES AND COMPARISON WITH BR-202

(Based on our investigations of BLAST program structure and unavailability of detailed program documentation the following is requested to be the revised scope of Task 2).

The purpose of this task is to implement an interface between the DOE-1 program and the BLAST program and compare the pulse generated results of BLAST with that of the NRC program BR-202 which is the basis of the weighting factors used in ASHRAE and DOE-1 load calculations.

- a. Implement a method for generating pulses on room surfaces and room air in BLAST due to radiative, conductive and convective loads. This will include direct and diffuse solar radiation, loads due to equipment, lights, external and internal surfaces and occupancy. Document changes made to BLAST.

- b. Establish methods for converting the pulse generated results from BLAST to the pretabulated weighting factor form for entry into DOE-1.
- c. Implement a method for entering weighting factors into DOE-1 and modify the Loads & Systems Programs so that the new weighting factors are used in the calculations when provided.
- d. Compare pulse generated results of BR-202 with that of BLAST. The intent here is to establish a base of reference to previously published work done at NRC, ASHRAE and NBS and identify and, if feasible, reconcile differences in results produced by BLAST program. If the difference in results cannot be explained at this time, recommendations will be made either to investigate this problem further or to bypass it with the development of parallel thermal balance routines in DOE-1/2.
- e. Utilize specific weighting factors developed for the test rooms in DOE-1 and compare with results of the pretabulated weighting factors in the previously divergent cases.

TASK 3 - DEVELOPMENT OF ANALYTIC RELATIONSHIPS BETWEEN THE THERMAL BALANCE AND THE WEIGHTING FACTOR TECHNIQUES

- a. Develop analytical expressions from a very simple model for the weighting factors to establish their functional dependence on room parameters and surface thermal properties.
- b. Compare the analytical forms to results obtained from an equivalent RC circuit in both continuous and sampled forms.

These two subtasks are preliminary to a thorough understanding of the relationship between the thermal balance and weighting factor methods and will provide a direction for the parametric tests in subtask 1, c. and possibly clarify the differences observed among BLAST and BR-202 program results of subtask 2, d.

- c. Investigate the use of perturbation techniques in more complex cases to relate the radiation coupled matrices to vector forms, i.e. thermal balance requires the solution of a radiation coupled matrix which is used to provide a solution to a unit pulse input, this result is then used as the coupling mechanism in the weighting factor technique. Use matrix perturbation methods to provide at least to first order the functional dependence of weighting factors to room parameters.
- d. Investigate the possibility of establishing weighting factors from room parameters either directly or with the use of a pretabulated set with appropriate correction elements.

TASK 4 - DEVELOP AND EVALUATE ALTERNATE ANALYSIS TECHNIQUES

- a. Review methods for coupling passive solar elements with the thermal balance and weighting factor methods and identify the assumptions required for such coupling.
- b. Develop and compare linearly coupled forms against detailed simultaneous or iterative solutions.
- c. If the results of subtask (b) are not acceptable, investigate other coupling techniques that may be more appropriate. The goals here are to develop techniques that approach the accuracy of detailed thermal balance method and the computational efficiency of the weighting factor method.
- d. If time permits the feasibility of spectral methods will also be investigated as this method is the most efficient in contrast to the previously considered approaches.

TASK 5 - MULTIPLE THERMAL ZONE ANALYSIS

- a. Review multizone coupling techniques in state-of-the-art building energy analysis programs.
- b. Review interzone convection algorithms which couple zones through open doors, windows and by stack effect.
- c. Select a method for implementation which is compatible with the results of Task 4 and document.