SIMULATION OF THE TRANSIENT BEHAVIOR OF STRATIFIED AIR CONDITIONING SYSTEMS

by

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TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

CHAPTER I

INTRODUCTION

Recently there has developed increasing interest in air conditioning large industrial buildings and manufacturing facilities. This activity is due to reports of increases in worker productivity and reductions in absenteeism in air-conditioned surroundings (1). Concurrent with the increased use of air conditioning systems runs the desire to reduce the cost, both initial and operating, of these systems.

One proposed method of reducing plant cooling load, and therefore air conditioning system cost, is known as thermal stratification. A thermally stratified system operates by supplying conditioned air to only the lower occupied levels, known as the conditioned zone. The temperature of air above the conditioned zone, known as the stratified zone, is uncontrolled. At its lower boundary, the air temperature approaches the conditioned zone temperature and at the upper boundary it approaches the roof temperature. Hence the name thermal stratification.

It is currently believed that proper design of a stratified system will isolate certain loads (e.g., lighting loads, roof loads, and other load sources located in the stratified zone) from the plant cooling load.

Upon review of previous investigations in the area of cooling load reduction, the approaches taken can be separated into two general areas. One method essentially involves application of numerous methods of air conditioning load reduction (e.g., thermal storage, stratification, and spot cooling)

to a proposed building (2). The effects of these methods are then qualitatively estimated; savings from these systems is often reported to range from 30% to over 50%. As in many field investigations, these results are compared to poorly defined data, usually not noting all of the design parameters used to obtain the results.

Despite the general lack of quantitative evaluations of these systems, there are a number of them operating successfully (3). This success can, in most cases, be attributed to appropriate use of basic engineering judgement.

The other method of investigation attempts to discover the influence of geometric and load parameters on the temperature profile and cooling loads (3, 4, 5, 6, 7). One investigation was conducted under controlled steady-state load conditions in a scale model test chamber (5, 6). The model studies provided steady-state experimental temperature distributions under the actual range of operating conditions which occur in industrial plants.

Additionally, a computer model was developed to assist in analyzing the stratification process and to aid in experimental data reduction (5, 7). There appears to be reasonable correlation between the computed and experimental results.

Due to the steady-state load limitation of the previous investigation, it was proposed to extend this work to include non-steady-state load conditions. The purpose of the current work is to determine the transient effects of internal and external loads, supply, return, and ventilation rates, and also structural thermal storage on air temperature patterns and plant cooling load.

CHAPTER II

SYSTEM DESCRIPTION

To initiate discussion of a typical stratified air conditioning system, it is first necessary to identify the modes of energy transfer influencing the air temperature within the structure. Figure 1 is a representation of the energy and mass transfers included in the model developed here. These approximate the exchanges occuring in a typical installation.

The building envelope exchanges energy with the exterior environment by convection and radiation at the exterior roof surface and by transmission through the walls. For the exterior roof, radiation and convection effects (q_r) are combined in the model and treated purely as convection by the sol-air temperature (SAT) method (8). Figure 2 is a plot of the daily roof SAT and ambient air temperature patterns used in this analysis. Daily patterns may be adjusted according to building location.

For the walls, energy transfer by transmission (q_w) occurs between the ambient air and the air within the building. Transmission through the walls is approximated as occuring instantaneously (no storage) because of the common practice of employing low thermal mass walls in industrial building construction.

The plant cooling load is rejected to the ambient through the air conditioning system. Additionally, plant exhaust air ($\dot{m}_v$) and its associated energy may be rejected to the ambient via the ventilation system.

The floor slab conducts energy to the ground (q_f) beneath the slab. A relatively constant deep ground temperature is assumed for the transient conduction model of the floor slab.

Internally, the floor upper surface receives energy by radiation from the roof interior (q_{rr}) and from the lights (q_{lr}). The floor exchanges energy with the air in the conditioned space by convection (q_{fc}).

In addition to radiation to the floor, the interior roof surface exchanges energy by convection (q_{rc}) with air in contact with it in the stratified zone. Concentrated loads (q_{ic}) within the stratified zone contribute energy by convection to the air in this region.

The convective portion of the lighting load (q_{lc}) will be contributed to either the conditioned zone or the stratified zone depending upon the location of the lighting fixtures. Equipment and occupant loads (q_{id}) contribute energy by convection to the air within the conditioned zone.

If only the sensible portion of the energy transfer is considered, the energy balance of the entire system, shown in Figure 1, is as follows.

$$\dot{q}_r + \dot{q}_w + \dot{q}_{lc} + \dot{q}_{lr} + \dot{q}_{id} + \dot{q}_{ic} - \dot{q}_f - \dot{m}_v\ C\ T(M) - \dot{m}_r\ C\ T(MRET)$$

$$+ \dot{m}_s\ C\ TS = \frac{\Delta(\text{Energy Stored})_{\text{air, roof, floor}}}{\Delta\theta}.$$

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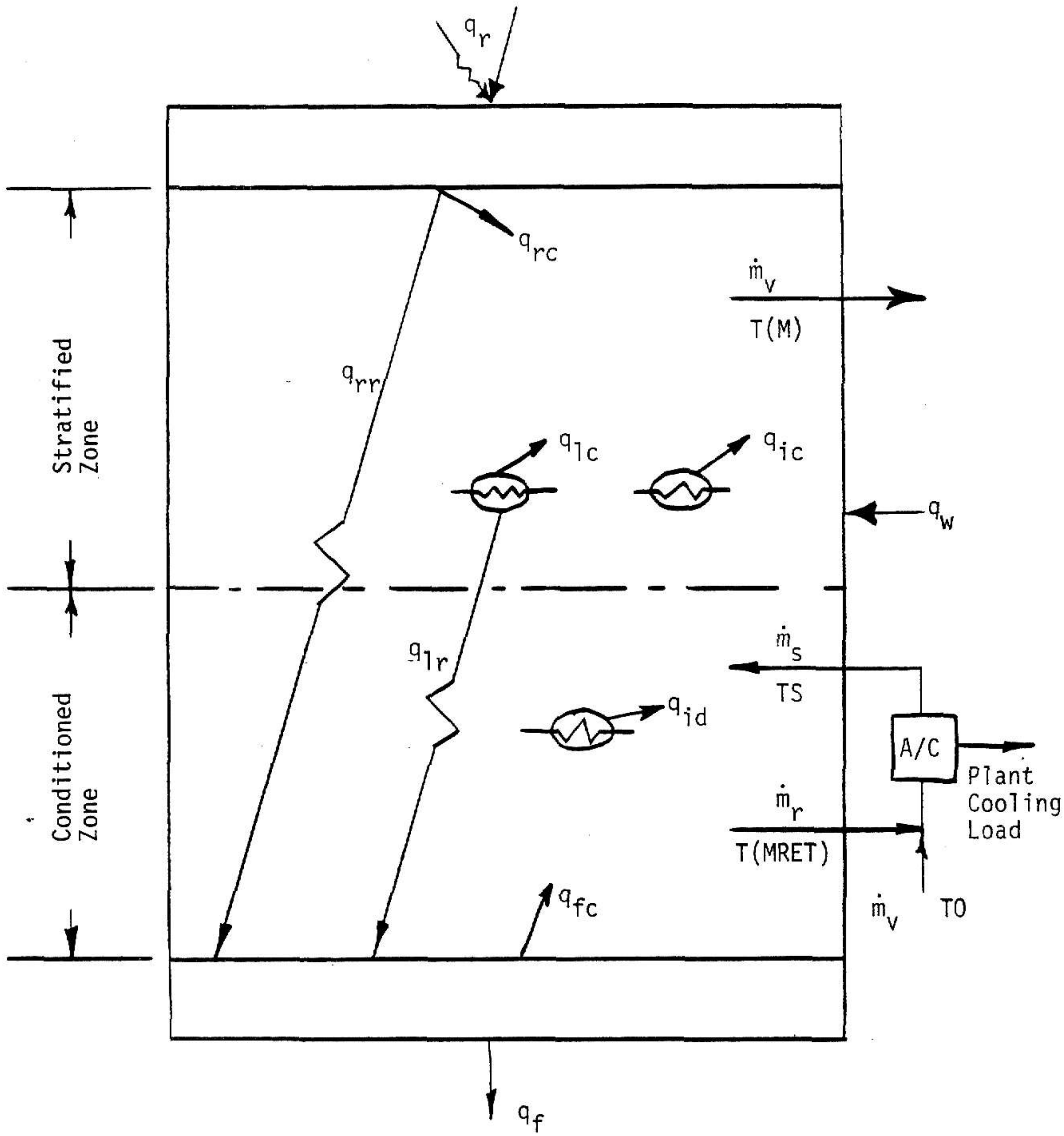

Figure 1. Energy and Mass Transfer Model as Approximated by the Computer Model.

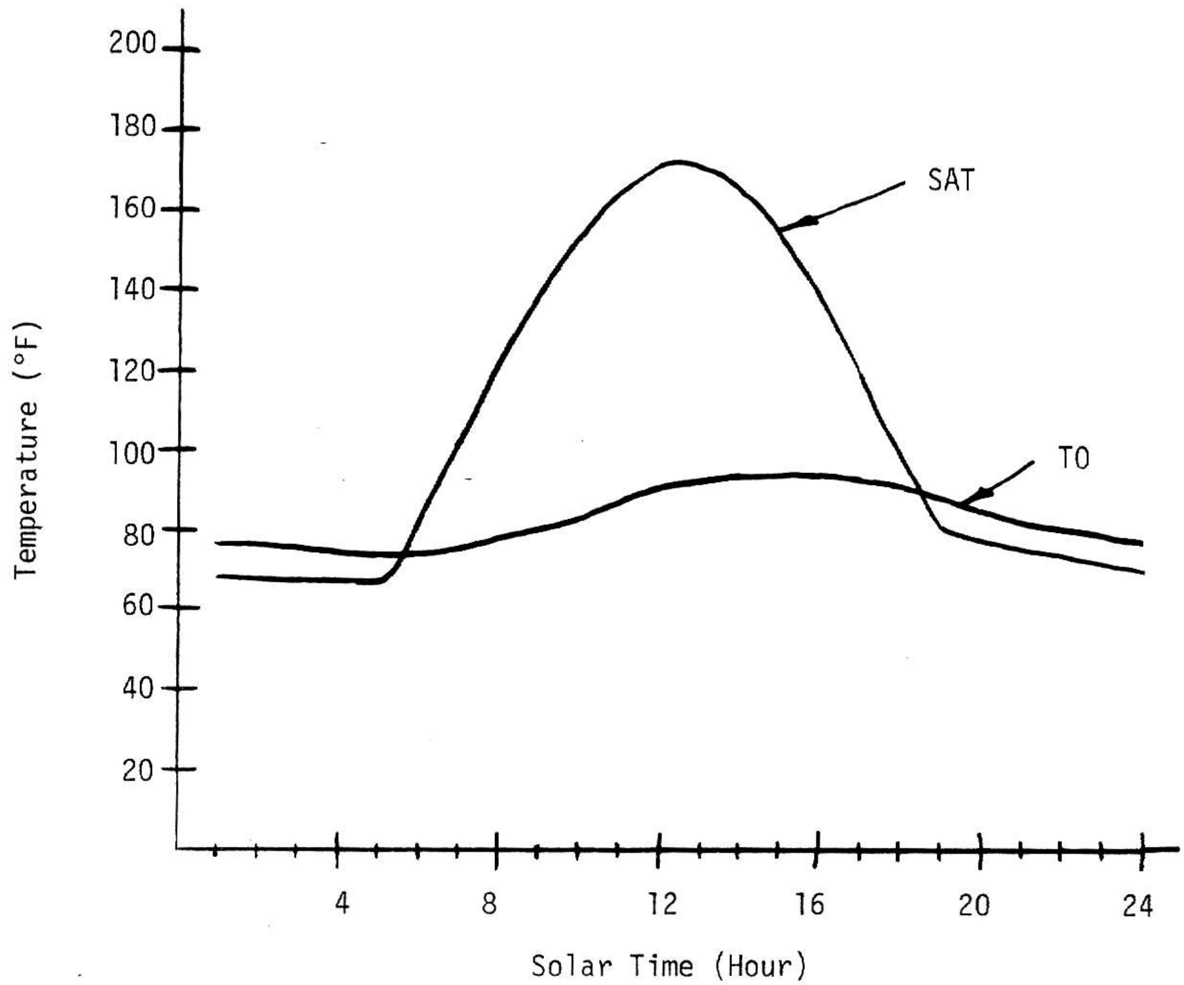

Figure 2. Daily Sol-Air and Ambient Air Temperatures.

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CHAPTER III

COMPUTER MODEL DESCRIPTION

The computer model development is discussed in five distinct sections: Finite-Difference Analysis, Mass Balance Model, Energy Balances of Air Elements, Energy Balances of the Roof and Floor Elements, and the Buoyancy Approximation. A complete listing of the computer program is contained in Appendix C.

The following assumptions, based on the results of experimentation with the scale model test chamber (5, 7), are employed in development of the transient model.

1. The boundary between the conditioned zone and the stratified zone is assumed to lie directly above the level at which supply air is introduced.

2. Supply air is assumed to be distributed "perfectly" among all air elements below the level of supply (i.e., it is distributed uniformly in the conditioned zone).

3. Consistent with the above assumption, all convective loads that originate below the level of supply will be distributed evenly in the conditioned zone.

The last two assumptions represent the well-mixed assumption which approximates a well designed distribution system.

Finite-Difference Analysis

Due to the complex nature of the boundary conditions present in this investigation, analytical methods of solution are not practical or possible. However, the numerical finite-difference method of approximation is both possible and convenient. These methods are particularly well suited for use with digital computers.

In this analysis, the in-plant air, roof, and floor are each subdivided horizontally into a number of smaller elements. Each element is then assigned a reference point at its center, beginning with Element (1) in the floor, and continuing sequentially through Element (II) at the outside roof surface. Each discrete element is assumed to have constant physical properties throughout.

The next step is to perform a fundamental energy balance upon each element previously determined. The general form of the energy balance used is: $E_{in} - E_{out} = \Delta E_{stored}$, where E_{in} and E_{out} will consist of energy transfer rates in the forms of conduction, convection, radiation, and bulk mass transfer. The ΔE_{stored} term is approximated in the following manner.

$$\Delta E_{stored} = \frac{T^{+}(I) - T(I)}{\Delta\theta} \rho \; C \; \Delta x \; .$$

Finite-difference equations for all elements constitute a system of simultaneous equations of the following form, with the past temperatures, T, included in the constants, C.

$$a_{1,1}\,T^+(1) + a_{1,2}\,T^+(2) + \ldots + a_{1,n}\,T^+(n) = C_1\,,$$

$$a_{2,1}\,T^+(1) + a_{2,2}\,T^+(2) + \ldots + a_{2,n}\,T^+(n) = C_2\,, \text{ and}$$

$$\vdots \qquad\qquad \vdots \qquad\qquad \vdots \qquad \vdots$$

$$a_{n,1}\,T^+(1) + a_{n,2}\,T^+(2) + \ldots + a_{n,n}\,T^+(n) = C_n\,.$$

Solution of the above simultaneous equations by the Gauss-Jordan reduction method will yield the temperature profiles in the floor, air, and roof at the completion of the desired time step.

Mass Balance Model

A mass balance is performed on the entire building to determine the ventilation flow rate ($\dot{m}_v$) from the supply ($\dot{m}_s$) and return ($\dot{m}_r$) flow rates. Supply air is distributed evenly among all air layers below the level of supply. Even distribution of air within the conditioned zone simulates the assumption of "perfect" air distribution and uniform mixing (5, 6). The supply air flow rate to each element is determined by: $\dot{m}_{se}(I) = \dot{m}_s/N$, where N is the number of air elements that receive supply air. The total building return air and total building ventilation air, are each extracted from individual air elements. The following element flow rates apply: $\dot{m}_{re}(MRET) = \dot{m}_r$ and $\dot{m}_{ve}(M) = \dot{m}_v$, where MRET and M are the integer number of the air elements where the system return and ventilation outlets are located.

Mass balances are applied to individual air elements. Supply, return, and ventilation flow rates for Element (1) have previously been determined as noted above. Refer to Figure 3 for the energy and mass transfer model of Air Element (1). Circulation with the element above ($\dot{m}_{ce}$) is the remaining unknown quantity, which can be calculated as follows.

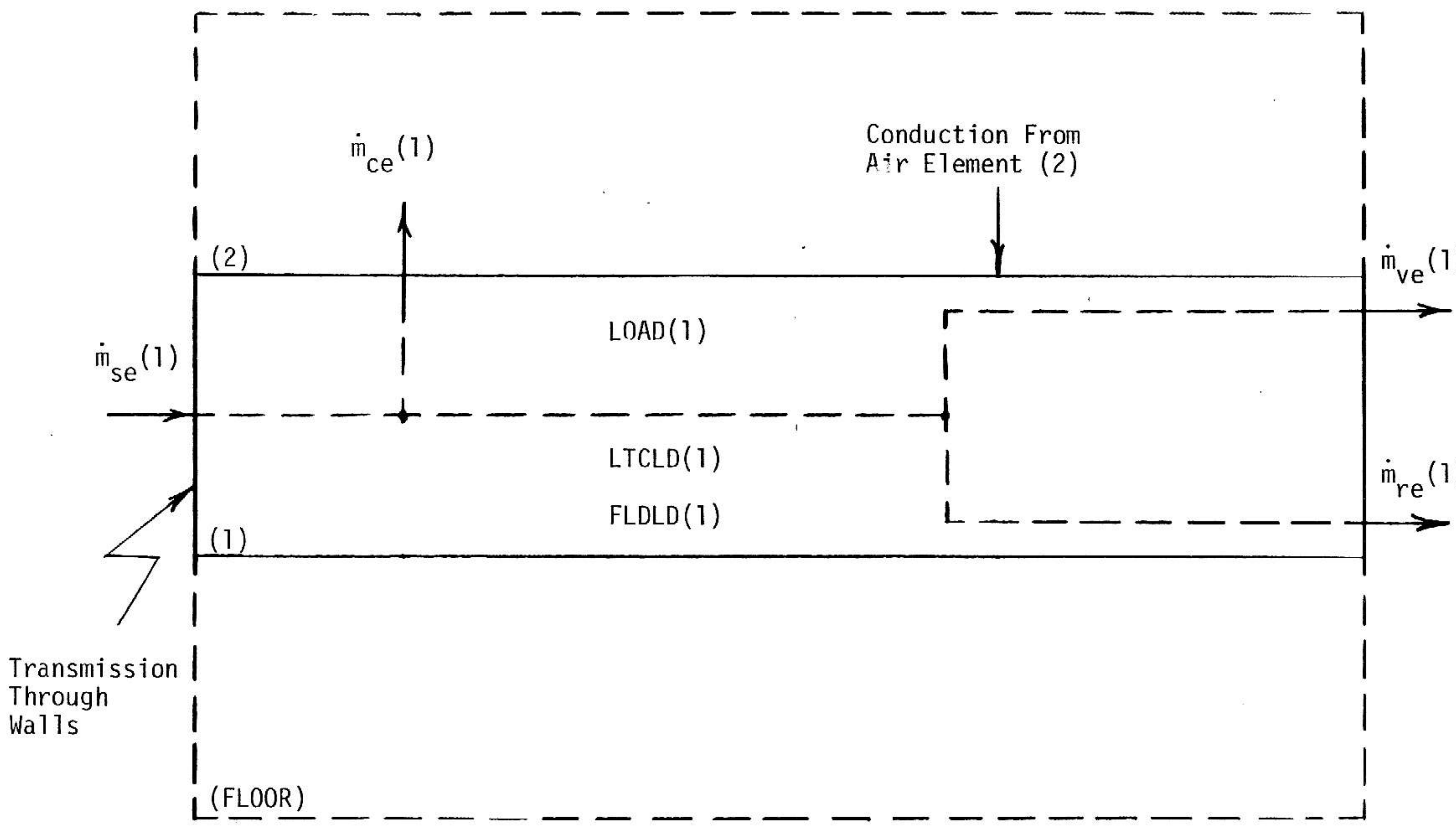

Figure 3. Energy and Mass Transfer Model of Air Layer Adjacent to the Floor.

$\dot{m}_{ce}(1) = \dot{m}_{se}(1) - \dot{m}_{re}(1) - \dot{m}_{ve}(1).$

In this equation, if MRET $\neq$ 1, then $\dot{m}_{re}(1) = 0$, and if M $\neq$ 1, then $\dot{m}_{ve}(1) = 0$. Refer to Figure 4 for the energy and mass transfer model of the typical air elements: Air Elements (2) through (K-1). Beginning with Air Element (2) and continuing through Air Element (K-1), circulation with the element above is calculated in the following manner.

$\dot{m}_{ce}(I) = \dot{m}_{se}(I) - \dot{m}_{re}(I) - \dot{m}_{ve}(I) + \dot{m}_{ce}(I-1).$

Energy Balances of the Air Elements

Figure 3 represents the energy and mass transfer model of the air element adjacent to the floor. The following modes of energy transfer influence the element.

Conduction, from Air Element (2), which is calculated by:

$$\frac{k + k_{mix}}{\Delta x} [T^{+}(NAIR + 1) - T^{+}(NAIR)],$$

where k is the thermal conductivity, k_{mix} is a macroscopic mixing parameter representing turbulent mixing effects, and where NAIR is the integer number of the first air element.

Transmission, through the walls, which is calculated by:

U_{wall} PER Δx [TO - T^{+}(NAIR)].

The term LOAD represents convection from heat sources located within this element.

The term LTCLD represents the convective portion of the lighting load, if the lights are located in this element. Consistent with the "perfect" air distribution assumption, LOAD and LTCLD are evenly distributed within the conditioned zone.

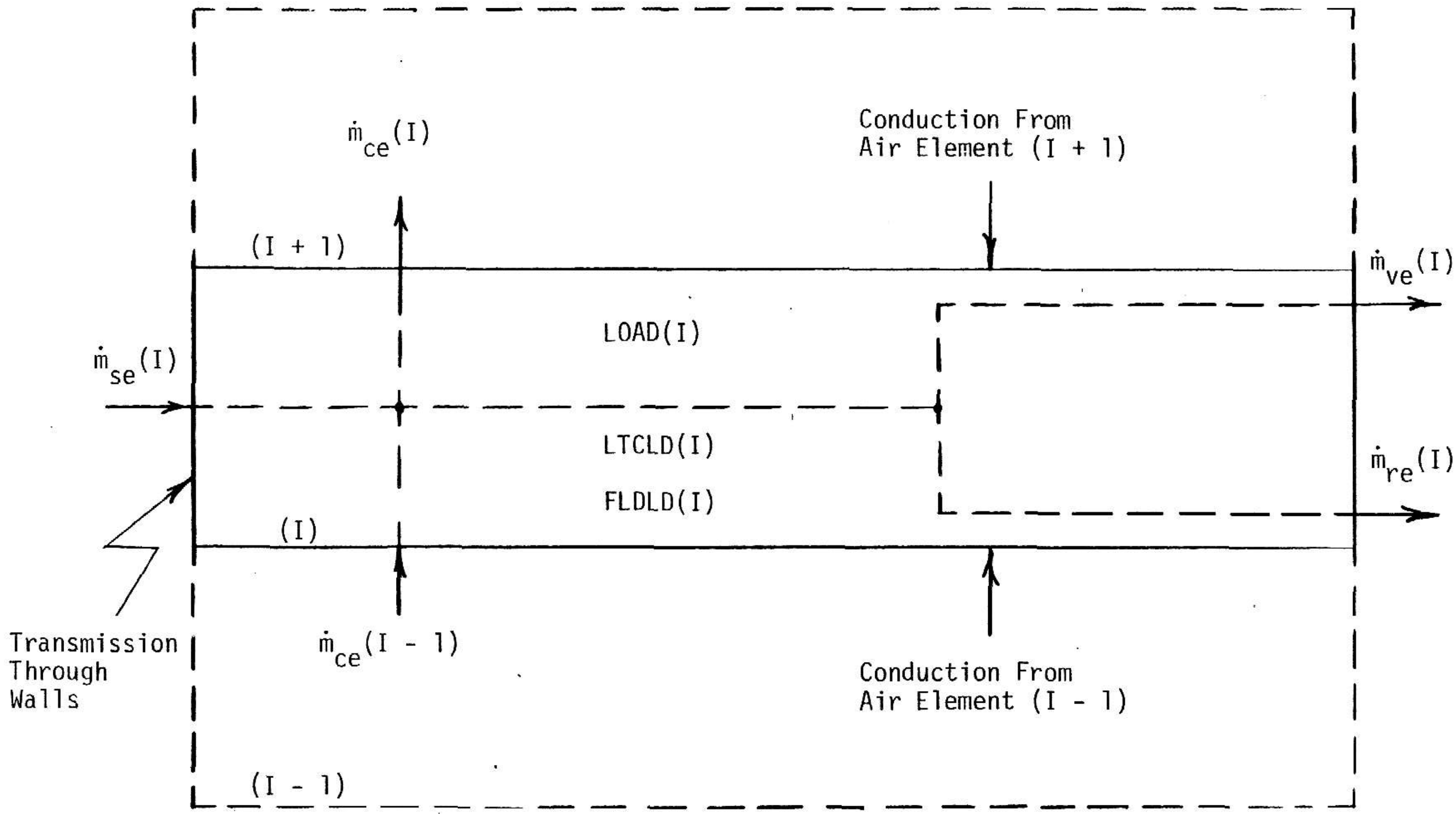

Figure 4. Energy and Mass Transfer Model of a Typical Air Element.

The term FLDLD represents the portion of the floor convective load which is distributed to each individual air element in the conditioned zone, consistent with the "perfect" air distribution assumption. FLDLD(1) can be computed by:

$$FLDLD(1) = \frac{h_{fi}}{N} [T^+(NFL) - T^+(NAIR)],$$

where the inside floor surface convection coefficient (h_{fi}) is calculated according to (9):

$$h_{fi} = 1.7[T(NFL) - T(NAIR)]^{.25} .$$

Energy transfer due to supply, return, and ventilation flows respectively, are calculated by:

$$\dot{m}_{se}(1)\ C\ TS,$$

$$\dot{m}_{re}(1)\ C\ T^+(NAIR), \text{ and}$$

$$\dot{m}_{ve}(1)\ C\ T^+(NAIR) .$$

The transient energy balance for Air Element (1) is written as follows.

$$\frac{T^+(NAIR) - T(NAIR)}{\Delta\theta} \rho\ C\ \Delta x = \dot{m}_{se}(1)\ C\ TS + LOAD(1) + FLDLD(1) + LTCLD(1)$$

$$+ U_{wall}\ PER\ \Delta x\ [TO - T^+(NAIR)] + \frac{(k + k_{mix})}{\Delta x} [T^+(NAIR + 1) - T^+(NAIR)]$$

$$- \dot{m}_{ve}(1)\ C\ T^+(NAIR) - \dot{m}_{re}(1)\ C\ T^+(NAIR) .$$

By defining:

$$C_1 = \frac{\Delta\theta}{\rho\ C\ \Delta x} ,$$

$$C_2 = \frac{\Delta\theta}{\rho\ \Delta x} ,$$

$$C_3 = \frac{U_{wall}\ PER\ \Delta\theta}{\rho\ C} ,$$

$$C_4 = \frac{(k + k_{mix})\ \Delta\theta}{\rho\ C\ \Delta x^2}\ , \text{ and}$$

$$C_5 = \frac{h_{fi}\ \Delta\theta}{N\ \rho\ C\ \Delta x}\ .$$

This can be rewritten:

$$T^+(NAIR)\ [1 + C_5 + C_3 + C_4 + C_2\ \dot{m}_{ve}(1) + C_2\ \dot{m}_{re}(1)] - T^+(NAIR + 1)\ [C_4]$$
$$- T^+(NFL)\ [C_5] = T(NAIR) + C_2\ \dot{m}_{se}(1)\ TS + C_1\ LOAD(1) + C_1\ LTCLD(1)$$
$$+ C_3\ TO\ .$$

Figure 4 represents the energy and mass transfer model of the typical air element. The result of the energy balance on this air element is given by:

$$T^+(I + NFL)\ [1 + C_3 + 2\ C_4 + C_2\ \dot{m}_{ve}(I) + C_2\ \dot{m}_{ce}(I) + C_2\ \dot{m}_{re}(I)]$$
$$+ T^+(NAIR)\ [C_5] - T^+(NFL)\ [C_5] - T^+(I - 1 + NFL)\ [C_2\ \dot{m}_{ce}(I - 1) + C_4]$$
$$- T^+(I + 1 + NFL)\ [C_4] = T(I + NFL) + C_2\ \dot{m}_{se}(I)\ TS + C_1\ LOAD(I)$$
$$+ C_1\ LTCLD(1) + C_3\ TO\ .$$

The air element adjacent to the roof is handled in a special manner due to the possible inclusion of the roof truss structure as a thermal storage mechanism in this element. Figure 5 represents the energy and mass transfer model of this element.

By defining:

$$C_6 = \frac{\Delta\theta}{[\rho\ C\ \Delta x + m_{tr}\ C_{tr}]}\ ,$$

$$C_7 = \frac{\Delta\theta}{[\rho\ \Delta x + m_{tr}\ C_{tr}]}$$

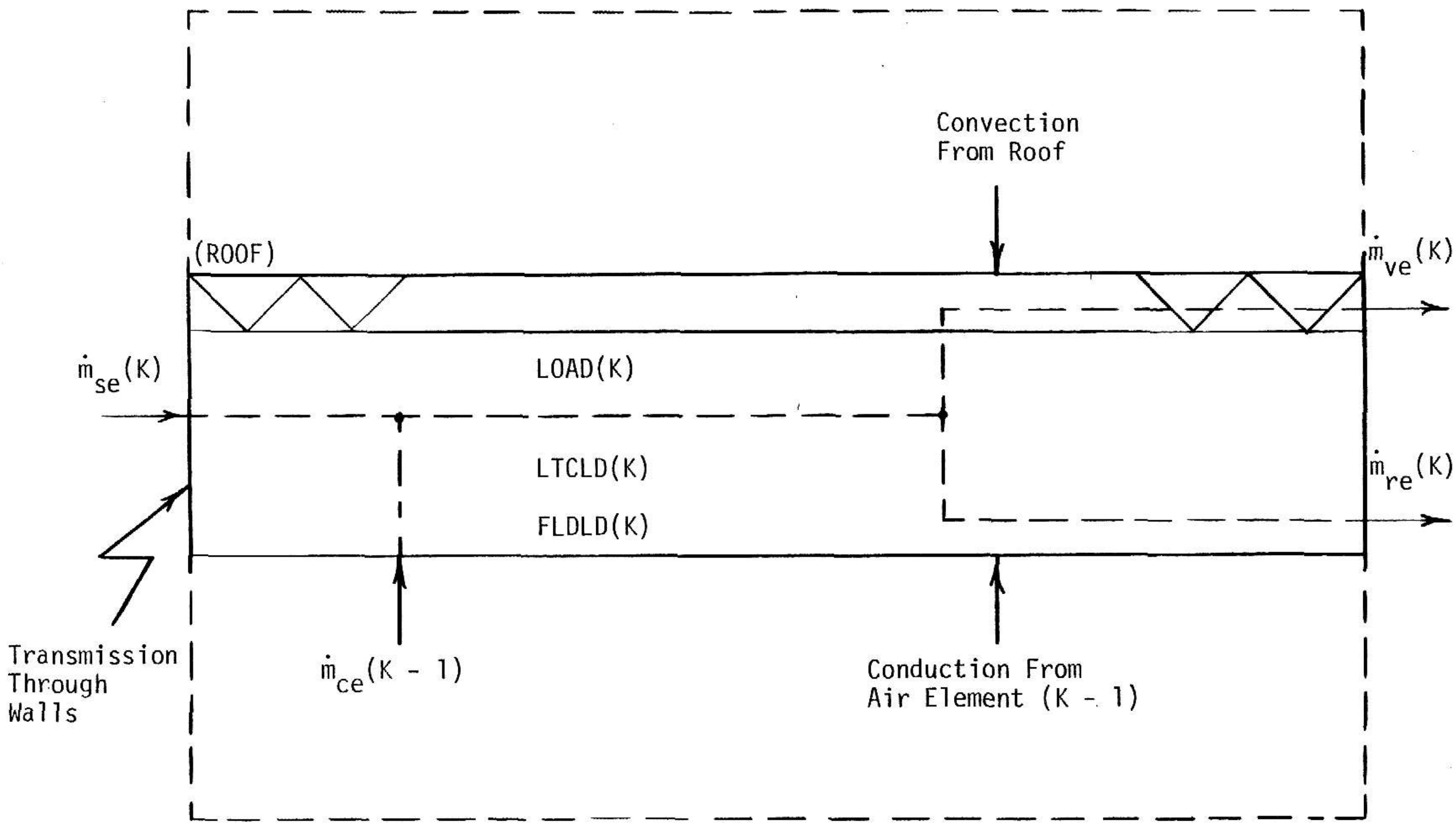

Figure 5. Energy and Mass Transfer Model of the Air Element Adjacent to the Roof.

$$C_8 = \frac{(k + k_{mix})\ \Delta\theta}{[\rho\ C\ \Delta x + m_{tr}\ C_{tr}\ \Delta x]}\ ,$$

$$C_9 = \frac{U_{wall}\ PER\ \Delta\theta\ \Delta x}{[\rho\ C\ \Delta x + m_{tr}\ C_{tr}]}\ ,$$

$$C_{10} = \frac{h_{ri}\ \Delta\theta}{[\rho\ C\ \Delta x + m_{tr}\ C_{tr}]}\ , \text{ and}$$

$$C_{11} = \frac{h_{fi}\ \Delta\theta}{N[\rho\ C\ \Delta x + m_{tr}\ C_{tr}]}\ ,$$

the energy balance of Air Element (K) can be written:

$$T^+(KAI)\ [1 + C_9 + C_8 + C_{10} + C_7\ \dot{m}_{ve}(K) + C_7\ \dot{m}_{re}(K)] + T^+(NAIR)\ [C_{11}]$$

$$- T^+(NFL)\ [C_{11}] - T^+(KAI + 1)\ [C_{10}] - T^+(KAI - 1)\ [C_8 + C_7\ \dot{m}_{ce}(K - 1)]$$

$$= T(KAI) + C_7\ \dot{m}_{se}(K)\ TS + C_6\ LOAD(K) + C_6\ LTCLD(K) + C_9\ TO.$$

Energy Balances of the Roof and Floor Elements

The roof and floor energy balances are handled in a similar manner, with the following exceptions.

1. Provisions have been made to allow for both the roof and floor to consist of a number of materials each with different thermal properties.

2. Each separate material consists of three elements arbitrarily chosen to include two surface nodes and one itnerior node.

Refer to Figures 6 and 7 for the energy transfer models of the roof and floor, respectively.

Consider the following constants for simplification of the energy balances of the roof elements.

$$D_1 = \frac{2\ h_{ro}\ \Delta\theta}{\rho_r\ C_r\ \Delta x_r}\ ,$$

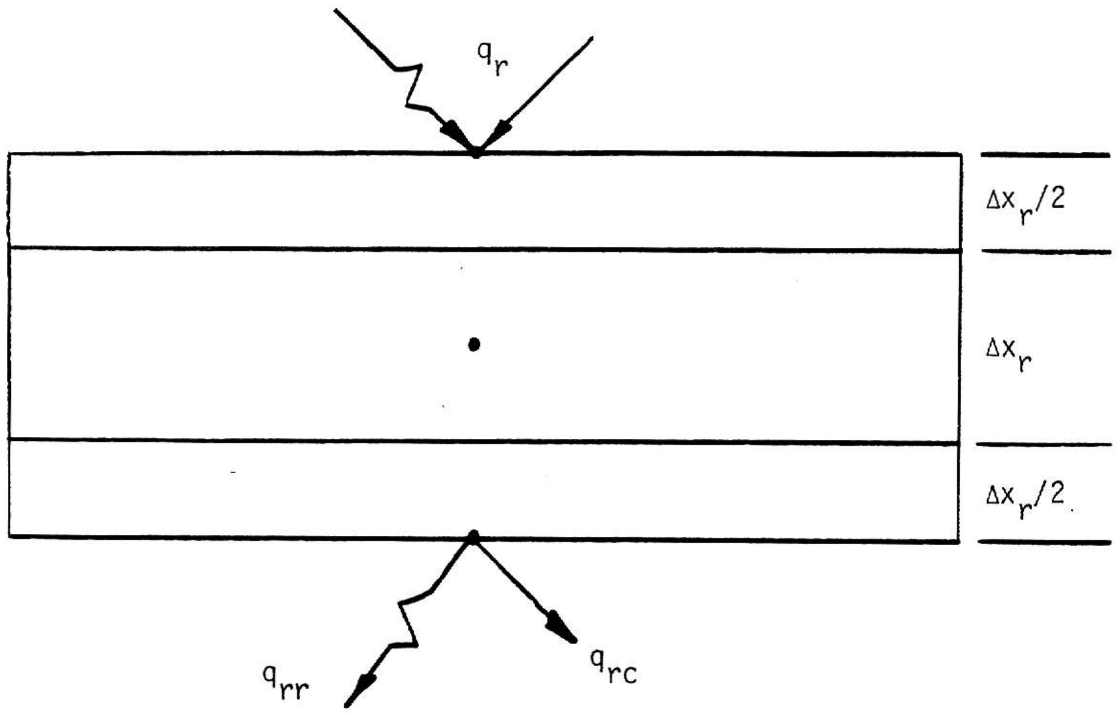

Figure 6. Energy Transfer Model of the Roof

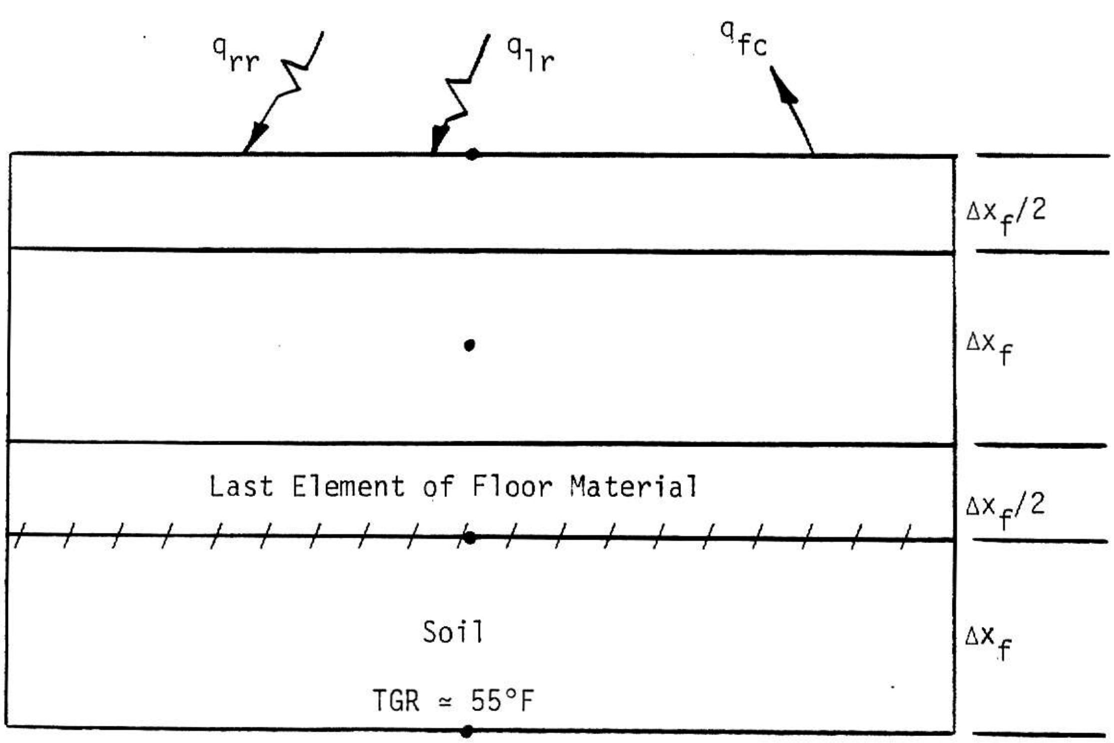

Figure 7. Energy Transfer Model of the Floor

$$D_2 = \frac{2\, k_r\, \Delta\theta}{\rho_r\, C_r\, \Delta x_r^2} ,$$

$$D_3 = \frac{2\, h_{ri}\, \Delta\theta}{\rho_r\, C_r\, \Delta x_r} , \text{ and}$$

$$D_4 = \frac{2\, \sigma_b\, SF\, \Delta\theta}{\rho_r\, C_r\, \Delta x_r} \frac{[(T(KAI + 1) + 460)^3 - (T(NFL) + 460)^3]}{(1/\varepsilon_1 + 1/\varepsilon_2 - 1)} .$$

Where the outside roof surface convection coefficient (h_{ro}) is given by (8): $h_{ro} = 3.0$, also, the inside roof surface convection coefficient (h_{ri}) is given by:

$$h_{ri} = A + (B\, (\dot{m}_{ve}(K)/C)^{.8}),$$

$A = .35,$

$B = .30,$ and

$C = 7.0$.

Constants A, B, and C were chosen by comparison of computed results with results from the steady-state experiments.

The constant D_4 is calculated based on the principles of thermal radiation between parallel plates with surface emissivities (ε_1, ε_2) and an angle factor which is equal to unity. The floor surface density factor (SF) is included to allow for approximating the net transfer of thermal radiation between the roof and floor, considering various densities of equipment on the floor (acting as radiation shields).

The energy balance of the outside surface roof element may be written:

$$T^+(II)\ [1 + D_1 + D_2] - T^+(II - 1)\ [D_2] = T(II) + D_1\ SAT.$$

Similarily, the energy balance of the inside surface roof element may be written:

$$T^+(KAI + 1)\ [1 + D_2 + D_3 + D_4] - T^+(NFL)\ [D_4] - T^+(KAI + 2)\ [D_2]$$

$$- T^+(KAI)\ [D_3] = T(KAI + 1)\ .$$

Consider next, the similar set of constants for use in the development of the energy balances of the floor elements.

$$E_1 = \frac{2\ k_f\ \Delta\theta}{\rho_f\ C_f\ \Delta x_f^2}\ ,$$

$$E_2 = \frac{2\ \Delta\theta}{\rho_f\ C_f\ \Delta x_f}\ ,$$

$$E_3 = \frac{2\ \sigma_b\ SF}{\rho_f\ C_f\ \Delta x_f}\ \frac{[(T(KAI + 1) + 460)^3 - (T(NFL) + 460)^3]}{(1/\varepsilon_1 + 1/\varepsilon_2 - 1)}\ , \text{ and}$$

$$E_4 = \frac{2\ h_{fi}\ \Delta\theta}{\rho_f\ C_f\ \Delta x_f}\ .$$

The following equation represents the simplified energy balance of the inside surface floor element.

$$T^+(NFL)\ [1 + E_1 + E_3 + E_4] - T^+(NFL - 1)\ [E_1] - T^+(KAI + 1)\ [E_3]$$

$$- T^+(NFL + 1)\ [E_4] = T(NFL) + E_2\ LTRLD.$$

With the constant ground temperature boundary condition, the energy balance of the first floor element is written in the following manner.

$$\frac{T^+(1) - T(1)}{\Delta\theta}\ \frac{\Delta x_f}{2}\ \rho_f\ C_f = \frac{k_f}{\Delta x_f}\ [T^+(2) - T^+(1)] + \frac{k_s}{\Delta x_f}\ [T_{gr} - T^+(1)].$$

By defining:

$$E_5 = \frac{2\ k_s\ \Delta\theta}{\rho_f\ C_f\ \Delta x_f^2}\ ,$$

this can be rewritten:

$$T^+ [1 + E_1 + E_5] - T^+(2) [E_1] = T(1) + E_5 T_{gr} .$$

Continuing in the same manner as with the surface elements, energy balances are next performed on interior roof and floor elements. The following equations represent the simplified energy balances of the interior roof element and interior floor element respectively.

$$T^+(II - 1) [1 + D_2] - T^+(II) [D_2/2] - T^+(II - 2) [D_2/2] = T(II - 1), \text{ and}$$

$$T^+(2) [1 + E_1] - T^+(1) [E_1/2] - T^+(3) [E_1/2] = T(2) .$$

Hence the complete system of equations, in the desired form, that describe the relationships between the air, roof, and floor elements have been developed.

Buoyancy Approximation

The equations presented earlier have not accounted for mass flow of space air due to buoyancy effects. These flows occur when a fluid is locally heated which decreases the fluid density; differences in density are the driving forces behind buoyancy effects. Localized heating by convective heat transfer will possibly occur in the vicinity of lights or concentrated loads located in the stratified zone. "Perfect" air distribution will preclude the formation of buoyancy flows in the conditioned zone.

It is assumed that the buoyancy mechanism will operate naturally to prevent the formation of cool air layers above warm air layers.

Consistent with the above assumption, the following approximation is employed in place of a thorough buoyancy flow analysis. Upon determination of the temperature profile of the air elements, a check is made to locate an element whose temperature is greater than the one above. This condition would indicate that the buoyancy action should operate. If an inversion is found to exist, the temperatures of the involved elements are averaged in the following manner.

$$XX = \frac{T(I)\ YY(I) + T(I + 1)\ YY(I + 1)}{YY(I) + YY(I + 1)} ,$$

where:

$$YY(I) = \rho\ C\ \Delta x ,$$

or:

$$YY(K) = [\rho\ C\ \Delta x + m_{tr}\ C_{tr}] .$$

Next the temperatures of the two affected air elements are reassigned in the following manners.

$$T(I) = XX, \text{ and}$$

$$T(I + 1) = XX .$$

This pattern is then repeated until no further temperature inversions remain. This procedure is justified by noting that the one hour computational time step used tends to disguise the details of buoyancy transport and reports only the larger scale effect of the energy transport during the one hour period.

CHAPTER IV

VERIFICATION

Initial verification of the validity of the computed results has been carried out for two specific areas: verification of steady-state behavior, and no-load verification of transient behavior.

Verification of Steady-State Behavior

Comparison has been made to the actual temperature profiles acquired from the steady-state model studies (4, 5, 6); Figures 8, 9, and 10 illustrate this comparison. Measured experimental results are shown as discrete points, while the computed results are shown as solid lines.

The transient computer program was modified to allow for steady-state heat input to the inside surface roof and floor elements. This approximates the heat input from the roof and floor heating panels used in the steady-state experiments. Further, the thermal properties of the floor, roof, and wall were assigned so as to approximate the conditions in the scale model test chamber.

Figure 8 shows the comparison of computed and experimental results when the applied load is within the inside surface roof element; floor and lighting loads are zero. The curves show very good agreement within the conditioned zone. Reasonable agreement, within four degrees maximum, is also shown in the stratified zone. Very close correlation is also shown for the inside surface roof temperature.

Figure 9 shows the comparison between the experimental and computer results with a floor level load only; roof and lighting loads are zero. Computed results yield a four degree higher inside roof temperature and a maximum difference in air temperature of five degrees at the six foot level. Predicted air temperatures within the conditioned zone are within one degree of those obtained from the scale model test chamber.

Representing results with only a lighting load at the five foot level, Figure 10 shows the comparison between computed and experimental results. Temperature correlation within the conditioned zone is very good, within one degree throughout. Computed results yield a four degree lower inside roof temperature. Predicted air temperatures within the stratified zone are a maximum of ten degrees higher at the four foot level, which is below the lighting level, and a minimum of three degrees higher near the roof.

The above situations were analyzed to demonstrate that the transient computer program properly accounts for the effects of loads that originate internally in the air or at the roof or floor. In all cases, temperature agreement between the computed and experimental results within the conditioned zone was within one degree. Considering the situations with only floor and roof level loads, the accuracy of prediction indicates radiation from the roof to floor and convection into the conditioned zone are properly accounted for.

With only a lighting load applied (Figure 10), the computed vs. experimental temperature profiles differ by the greatest amount of all cases. The largest temperature difference occurs at the four foot level, one foot below the lighting level. This difference is probably due to the fact that the buoyancy approximation does not properly account for actual flows in the presence of a concentrated heat source. In the actual case, buoyant plume

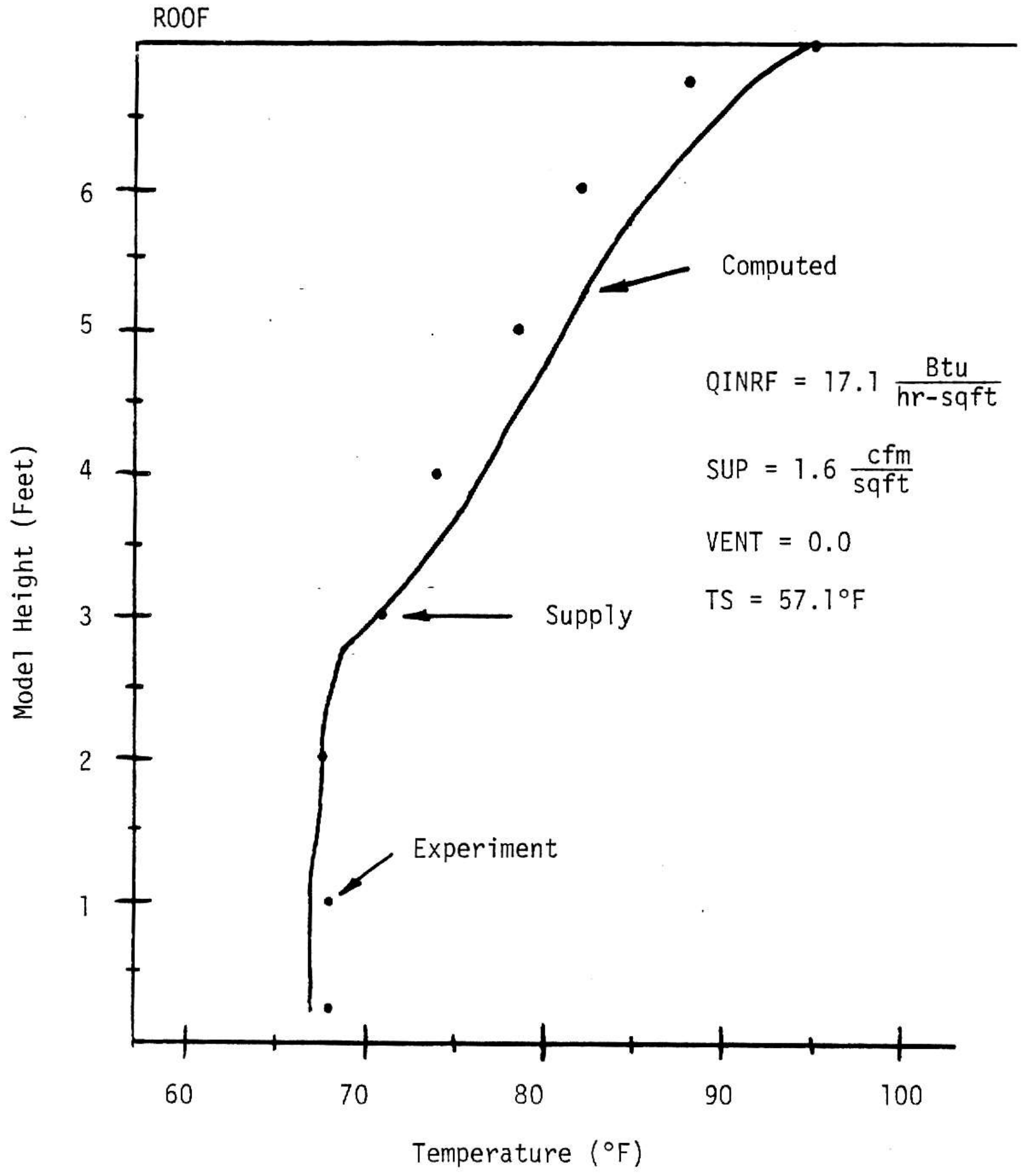

Figure 8. Comparison of Computed and Measured Results; Roof Load Only.

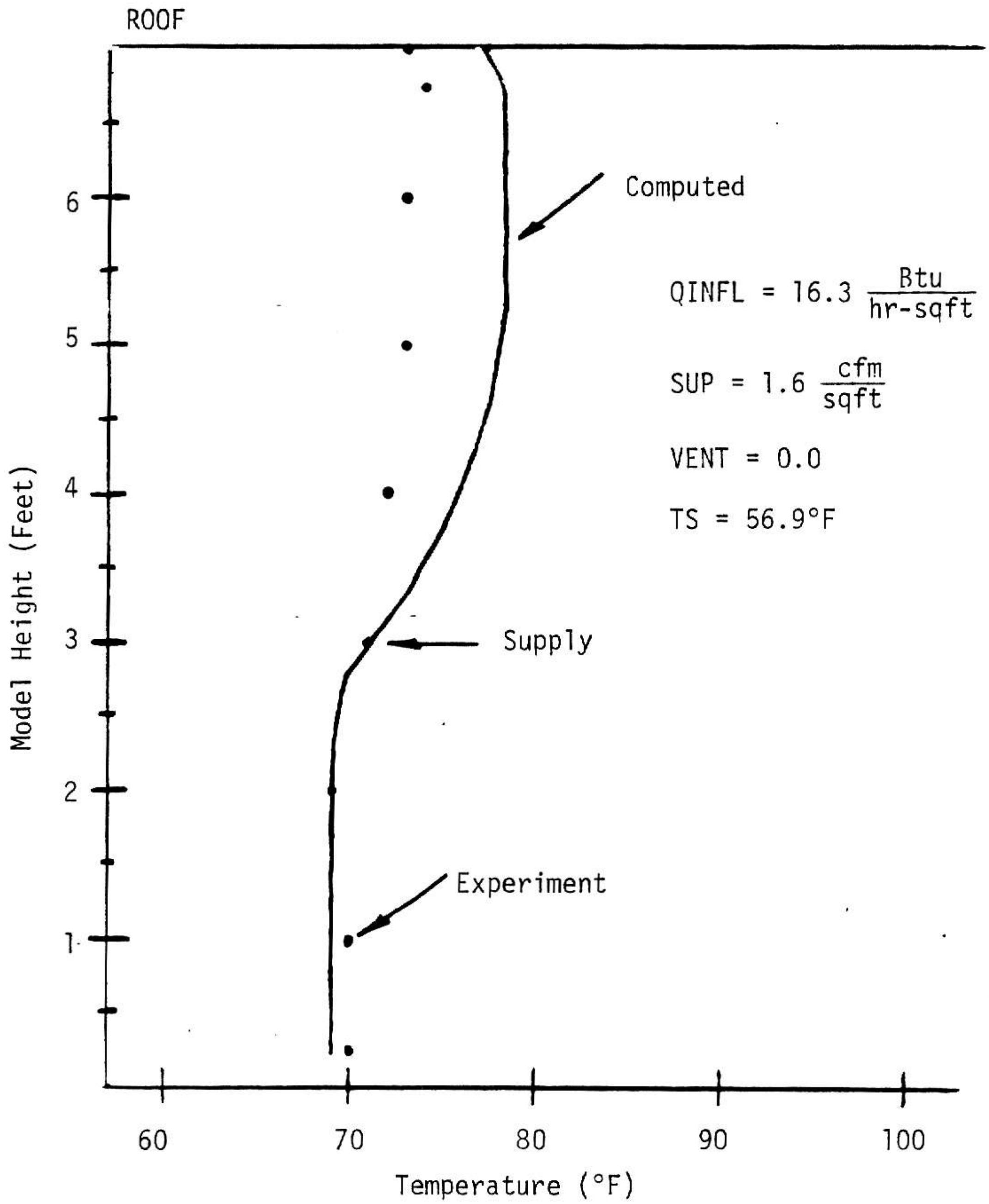

Figure 9. Comparison of Computed and Measured Results; Floor Load Only.

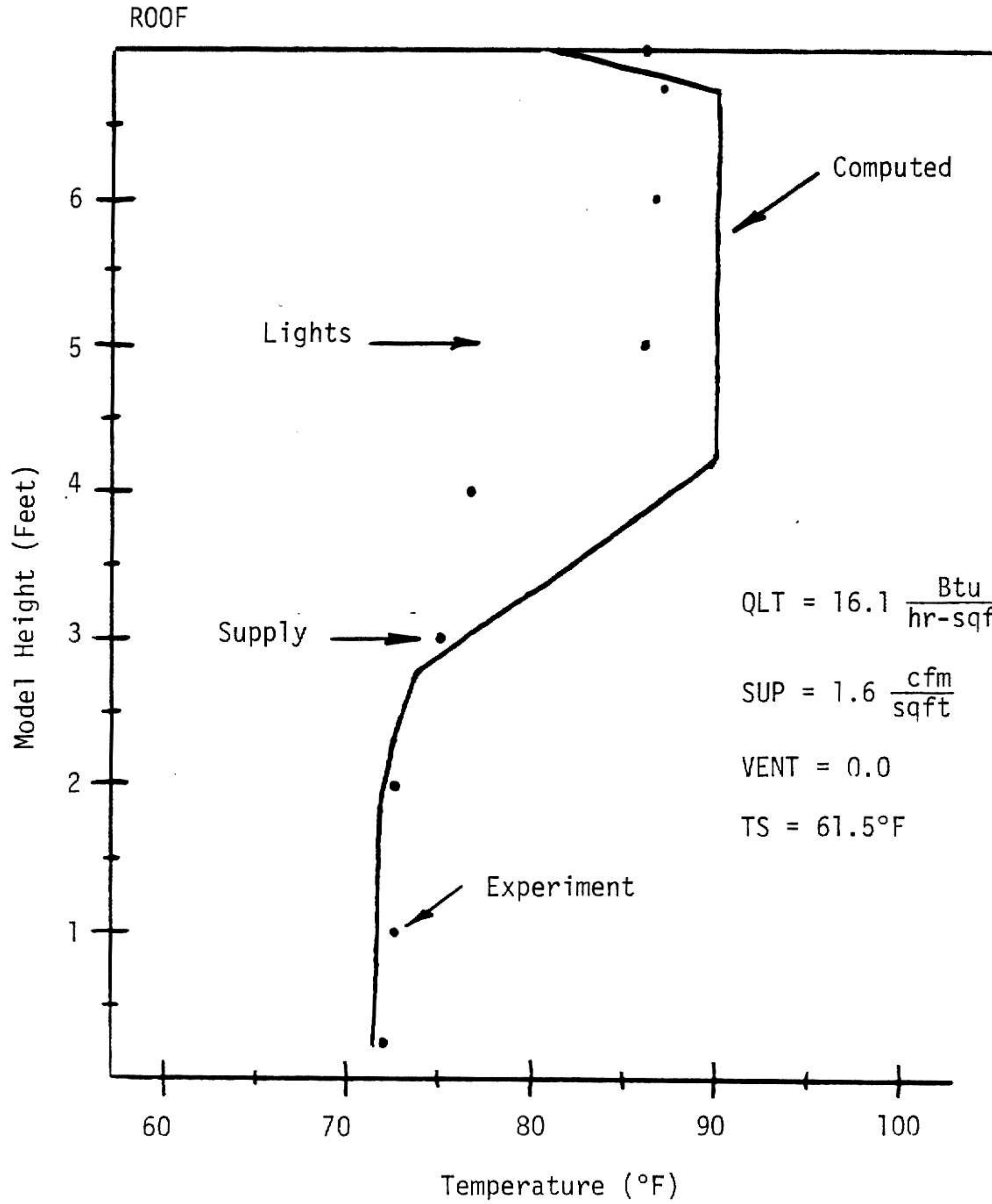

Figure 10. Comparison of Computed and Measured Results; Lighting Load Only.

originates below the actual level of heating and causes mixing below the level of the lights.

These three cases are intended to demonstrate that the transient computer model adequately represents the influence of the three individually occurring load sources. A more extensive comparison of experimental results and the referenced steady-state program, has been reported (5, 7). The previous report covers many more comparison cases for both individual load sources and combined load effects. The authors of that study concluded that the computed results provide an "adequate" representation of the experimental results for all cases investigated.

An extensive comparison of the transient program results to the steady-state program results was performed, but not reported here. The general conclusion was that the transient program and the steady-state program developed previously (5, 7), are accurate predictors of the internal conditions present in a stratified air conditioning system.

No-Load Verification of Transient Behavior

A trivial case with no internal loads has been investigated to verify the behavior of the computer program under transient conditions. The roof and air temperatures were initially set at 80°F while the floor was initialized at 55°F. Outside air temperatures and the supply air temperature were also set at 55°F. The supply air flowrate used was .25 cfm/sqft.

Figure 11 shows the variation of the building temperature profile as a function of time. Curves are presented to represent the initial conditions (t = 0), as well as the conditions after six hours (t = 6), and after twenty-four hours (t = 24).

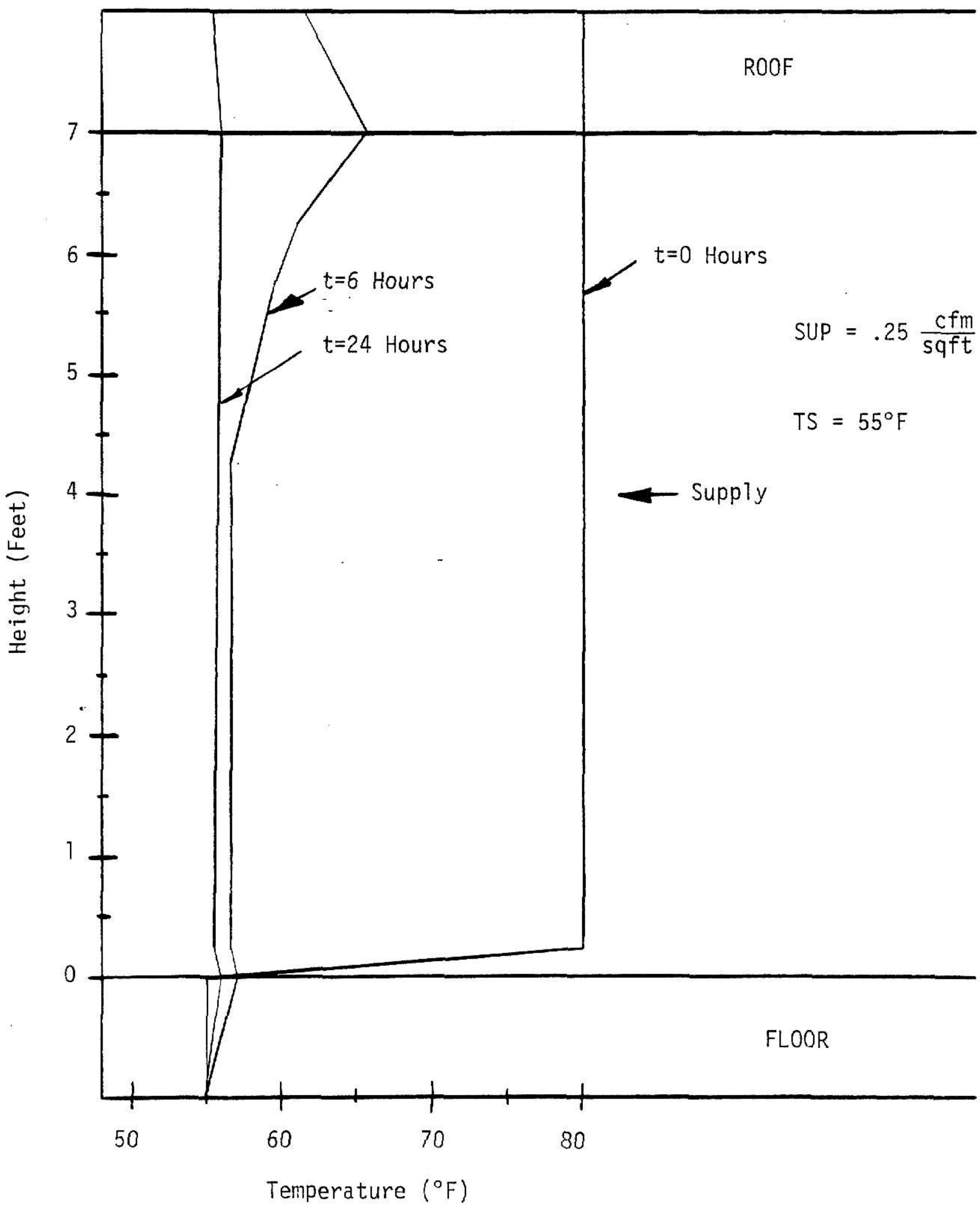

Figure 11. Transient No-Load Behavior.

Due to the constant 55°F applied sol-air temperature, the exterior roof surface experiences a faster rate of cooling than does the interior roof surface which exchanges energy with the space air and also the upper floor surface. After six hours (t = 6), the temperature of the air in the stratified zone approaches the conditioned zone temperature at it's lower boundary, and approaches the roof temperature at it's upper boundary.

Considering the boundary conditions present, it is expected that the entire building temperature profile would eventually approach a uniform temperature of 55°F. This condition is reasonably approximated after twenty-four hours (t = 24).

CHAPTER V

COMPUTED RESULTS

The computed results discussed in this section were chosen to illustrate the effects of system variables on the peak plant cooling load (required capacity of the cooling equipment) and the total daily rejected cooling load (daily cooling system energy usage). Additionally, the time at which the peak plant cooling load occurs is reported. The system variables investigated were: supply air inlet height, return air extraction height, roof construction, lighting height, ventilation air extraction height, ventilation air flow rate, and occupancy patterns. A detailed description of all cases investigated is contained in Appendix B.

The temperatures of all elements (roof, air, and floor) were initialized (T(I)) and the temperatures of all elements at the end of the computational time step were calculated. Iterations in time, using hourly temperature, load, and flow rate patterns, were continued until hourly temperature profiles indicated a daily periodic pattern had been obtained which was independent of the initial condition.

A constant roof height of twenty feet was used throughout the transient portion of this investigation. Effects of variable roof height were discussed in detail in the previous steady-state investigation (5, 7).

A Δx of two feet for the air elements was used throughout this investigation. Average internal load values, lighting (8.0 Btu/hr-sqft) and equipment (30.0 Btu/hr-sqft), were chosen from typical values in the literature. Equipment loads include the convective portion of both equipment and occupant loads.

The supply air flow rate was adjusted to maintain the conditioned space air temperature in the range 75°F-78°F while occupied. A supply air temperature of 55°F was used during periods of occupancy.

During periods of non-occupancy, where possible, 100% make-up air is introduced into the space to dissipate residual loads; space air temperature is maintained in the range 80°F-85°F, by varying supply air flow rate.

In all cases investigated, an incidental portion of the supply air was extracted as ventilation (to remove odors and fumes). Additionally, higher rates of ventilation flow were also investigated to establish the influence of ventilation rate on load.

Calculated results are discussed in related groups and the effects of system variables on air conditioning loads are determined.

Effect of Supply Air Inlet Height

Computed results of the effects of supply air inlet height on the plant cooling loads are shown in Table 1. The complete range of supply air inlet heights, Case 5 (supply at the ten foot level) to Case 3 (total volume --- supply to entire building), were investigated. In addition, an intermediate case, Case 10 (supply at the eighteen foot level), was investigated.

For all three cases, the return is located at the floor. Ventilation air for these cases is extracted directly below the roof.

If conditioned air is supplied to the entire building (total volume system) the interior convective roof load becomes a portion of the plant cooling load (in contrast to the stratified system, where the convective load is blocked as discussed below). In addition, a lower inside surface roof temperature occurs. This lower temperature promotes added heat transfer from the ambient into the space.

In addition to the roof convective load, a small amount of energy due to heat transmission through the walls is added to the plant cooling load. In the case of the total volume cooling system, the added heat load due to wall transmission amounted to only 0.4 Btu/hr-sqft (0.6%) of the peak plant cooling load. The wall transmission load is small compared to the peak plant cooling load, therefore, it is not discussed in further cases.

Also, a part of the plant cooling load in the total volume system is the convective portion of the lighting load. Although this load is also relatively small, when supply air is introduced at the roof, there is no other choice except to locate the lights within the conditioned zone.

Comparison of Case 3 (total volume system) to Case 10 (supply to eighteen foot level) yields a 44.0 Btu/hr-sqft (45%) reduction in peak plant cooling load, accompanied by a 286.9 Btu/sqft (36%) reduction in total daily rejected cooling load. If the supply air inlet height is further lowered to the ten foot level (Case 5), an additional reduction in peak plant cooling load of only 1.0 Btu/hr-sqft will occur, accompanied by an 8.2 Btu/sqft total daily rejected cooling load reduction. This additional small change is due to the decreased temperature gradient between the upper air element in the conditioned zone, and the lower air element in the stratified zone.

Overall reductions in plant cooling loads from Case 3 to Case 5 were: 45 Btu/hr-sqft (46%) in peak plant cooling load (required capacity of cooling equipment), and 295.1 Btu/sqft (38%) in total daily rejected cooling load (daily cooling system energy usage).

From these examples it is abundantly clear that by supplying conditioned air below the actual roof height (even only two feet below as in Case 10), as opposed to supplying conditioned air to the entire system (as in Case 3), there are enormous plant cooling load savings to be realized. For actual system design purposes, this indicates that every effort must be made to allow formation of a stagnant, warm air layer immediately adjacent to the interior roof surface. Presence of this layer prevents convective cooling of the roof and thus "blocks" the convective portion of the roof load which occurs in the total volume system.

TABLE 1

EFFECT OF SUPPLY AIR INLET HEIGHT ON PLANT COOLING LOADS

Case No.	Supply Air Inlet Height (Feet)	Time Of Peak Plant Cooling Load (Hour)	Peak Plant Cooling Load (Btu/hr-sqft)	Total Daily Rejected Cooling Load (Btu/sqft)
5	10.0	17	53.3	485.5
10	18.0	17	54.3	493.7
3	20.0	17	98.3	780.6

Effect of Return Air Extraction Height

The cases run in this section were intended to compare the effect of the position of the return air duct on the plant cooling loads. The effects of return air heights of nineteen feet (Case 7), five feet (Case 6), and one foot (Case 5) were investigated. Air supply height was ten feet. Table 2 lists the computed results for all three cases investigated.

Results of the previous experimental steady-state model studies (5, 6) indicated that the return air duct location had no effect upon the temperature profile in the space, as long as the return was located in the conditioned zone. Computed results of Cases 5 and 6, return located in the conditioned zone, indicate that only negligible changes occur in the plant cooling loads when changes of return location within the conditioned zone occur. Results of the transient computer program, therefore, corroborate the results presented previously.

If, however, the return air duct is located directly below the roof, as is often considered standard practice with roof-top units, the plant cooling loads increase dramatically. Although the temperature of the conditioned zone is not affected appreciably by the return location, if the duct is located directly below the roof (Case 7) the desirable stagnant air layer is destroyed and the convective portion of the roof load is added to the plant cooling load.

Due mainly to the isolation of the convective roof load from the return air, the peak plant cooling load is reduced 12.2 Btu/hr-sqft (18%), from Case 7 to Case 6, with a 98.4 Btu/sqft (16%) reduction in total daily rejected cooling load.

In general, it can therefore be concluded that return air duct height is an easily controlled system variable that allows reduction of plant cooling loads.

TABLE 2

EFFECT OF RETURN AIR EXTRACTION HEIGHT ON PLANT COOLING LOADS

Case No.	Return Air Extraction Height (Feet)	Time Of Peak Plant Cooling Load (Hour)	Peak Plant Cooling Load (Btu/hr-sqft)	Total Daily Rejected Cooling Load (Btu/sqft)
5	1.0	17	53.3	485.5
6	5.0	17	54.1	501.3
7	19.0	16	66.3	599.7

Effect of Roof Construction

The purpose of this section is to determine the influence of roof construction on plant cooling loads. Table 3 lists the computed plant cooling loads for all four cases. Four different roof construction techniques were investigated.

1. Case 8 - Nine inches of concrete with two inches of insulation.
2. Case 5 - Four inches of concrete with two inches of insulation.
3. Case 4 - Steel sheet with two inches of insulation.
4. Case 25 - Steel sheet with no insulation.

Essentially, the effects of two separate system variables were analyzed. Cases 4 and 25 investigate the effects of roof insulation on the plant cooling loads, while Cases 4, 5, and 8 investigate the transient effects of thermal roof mass on plant cooling loads.

For the four cases investigated, supply air is distributed at the ten foot level.

Recently there is renewed interest in insulating the exterior envelope of buildings. However, the relative energy savings are rarely more pronounced than when insulation is added to the exterior roof surface of an air-conditioned building. With only the addition of a two inch insulation layer, the peak plant cooling load was reduced, from Case 25 to Case 4, by 18%. Furthermore, the total daily rejected cooling load (daily cooling system energy usage) was reduced by 21%.

By adding insulation (low thermal conductivity material) to the exterior roof surface, a higher exterior roof temperature is possible without affecting the interior surface roof temperature. The elevated exterior roof surface temperature promotes added convective heat transfer to the surroundings which reduces the heat load imposed on the building.

Due to the low thermal mass of the steel sheet roof (Case 25), the peak plant cooling load occurs coincidentally with the peak sol-air temperature at hour fifteen (3 p.m.), whereas the peak plant cooling load in Case 4 is delayed by one hour until hour sixteen (4 p.m.). The time of occurance of the peak plant cooling load may be used beneficially in conjunction with occupancy patterns to achieve a large reduction in peak plant cooling load.

Cases 4, 5, and 8 were investigated to determine the effects of roof mass (thermal storage) on plant cooling load. With these cases it can be seen that by increasing the roof mass, both the peak plant cooling load and the total daily rejected cooling load can be reduced.

It is currently believed, and verified by this group of cases, that some energy from solar loads, ambient convective loads, and to a limited extent, internal loads, can be stored in the roof and released at a later time. This thermal storage effect would account for the decrease from Case 8 to Case 4 of 8.6 Btu/hr-sqft (15%) in peak plant cooling load, and in the decrease of 47.6 Btu/sqft (9%) in the total daily rejected cooling load. Furthermore, this storage effect would account for the delay in time of occurance of the peak plant cooling load.

In general, it can be concluded that these roof construction features, insulation and thermal mass, can provide reduction of the plant cooling loads.

TABLE 3

EFFECT OF ROOF CONSTRUCTION ON PLANT COOLING LOADS

Case No.	Roof Construction	Time Of Peak Plant Cooling Load (Hour)	Peak Plant Cooling Load (Btu/hr-sqft)	Total Daily Rejected Cooling Load (Btu/sqft)
8	Heavy roof, with insulation.	17	49.5	476.1
5	Medium roof, with insulation.	17	53.3	485.5
4	Light roof, with insulation.	16	58.1	523.7
25	Light roof without insulation.	15	70.9	666.9

Effect of Lighting Height

Transient Cases 5 and 19 were investigated to determine the influence of light height on plant cooling load. The convective portion of the lighting load (here assumed to be 20% of the total lighting load) is contributed to either the conditioned zone or the stratified zone depending upon the location of the lighting fixtures. The convective portion of the lighting load (1.6 Btu/hr-sqft) is only a small portion of the total internal load (30.0 Btu/hr-sqft), and an even smaller portion of the total imposed load. The radiant portion of the lighting load (80% of the total lighting load) will strike and be absorbed by interior surfaces irrespective of the light height.

Table 4 lists the computed plant cooling loads for Case 5 (lights in the stratified zone) and Case 19 (lights in the conditioned zone). For both cases the supply air is distributed at the ten foot level.

The peak plant cooling load occurs for both cases during hour seventeen (5 p.m.). It can be seen that the lighting height has an almost direct additive effect on both the peak plant cooling load and the total daily rejected cooling load.

If the lighting fixtures are located above the level of supply (in the stratified zone) a portion of the convective lighting load may be exhausted by ventilation air. The remainder of the convective lighting load may raise the air temperature within the stratified zone and the roof temperature, which will increase radiation to the floor and increase the plant cooling load.

Considering these cases it can be seen that the light height has only a negligible effect (less than 2%) on the peak plant cooling load, and also a negligible effect (6%) on the total daily rejected cooling load. However, if increased lighting loads were used, or internal loads were decreased, the effect of lighting height on air conditioning cooling load would become more pronounced.

TABLE 4

EFFECT OF LIGHTING HEIGHT ON PLANT COOLING LOADS

Case No.	Lighting Height (Feet)	Time Of Peak Plant Cooling Load (Hour)	Peak Plant Cooling Load (Btu/hr-sqft)	Total Daily Rejected Cooling Load (Btu/sqft)
5	12.0	17	53.3	485.5
19	10.0	17	54.4	518.4

Effect of Ventilation Air Extraction Height

The transient effects on plant cooling load of ventilation air extraction height were investigated. Using incidental ventilation only (0.1 cfm/sqft), Case 5 (ventilation directly below the roof) and Case 20 (ventilation at the twelve foot level) were computed for comparison purposes. For both cases, the supply air is distributed at the ten foot level. Table 5 lists the computed plant cooling loads for both cases.

One previous investigation into the design of stratified air conditioning systems (2) indicates that by ventilating near the roof (disturbing the stratified zone) the plant cooling load will be increased.

However, ventilating near the roof may in fact remove a portion of the convective loads affecting the stratified zone (e.g., convective lighting loads, concentrated loads). Furthermore, some cooling of the interior roof surface may occur. By reducing the interior surface roof temperature, radiation to the floor and thus the cooling load may be reduced.

Peak plant cooling load for both cases occurs during hour seventeen (5 p.m.). Although the peak plant cooling load reduction from Case 20 (ventilation at the twelve foot level) to Case 5 (ventilation directly below the roof) was only 1.6 Btu/hr-sqft (3% of the peak plant cooling load), and the reduction in the total daily rejected cooling load was only 38.4 Btu/sqft (7% of the total daily rejected cooling load), the effect of ventilation location may become more pronounced when increased convective loads are located in the stratified zone.

TABLE 5

EFFECT OF VENTILATION HEIGHT ON PLANT COOLING LOADS

Case No.	Ventilation Air Extraction Height (Feet)	Time Of Peak Plant Cooling Load (Hour)	Peak Plant Cooling Load (Btu/hr-sqft)	Total Daily Rejected Cooling Load (Btu/sqft)
5	19.0	17	53.3	485.5
20	12.0	17	54.9	523.9

Effect of Ventilation Rate

Cases 5, 21, and 22 were investigated to determine the effect of ventilation air flow rate on plant cooling load. Air that is extracted as ventilation must be replaced by make-up air; before make-up air is introduced into the conditioned space, it must be first cooled from the ambient air temperature (TO) to the supply air temperature (TS). Make-up air is, therefore, a portion of the plant cooling load.

Table 6 shows the computed plant cooling loads for Case 5 (incidental ventilation only), Case 22 (20% of supply flow to ventilation), and Case 21 (30% of supply flow to ventilation). Ventilation air is extracted for these cases directly below the roof. The remaining portion of the supply air is extracted through the return air system located at the floor. For all three cases investigated, supply air is distributed at the ten foot level.

Ventilation air may remove a portion of convective loads located within the stratified zone (e.g., lighting loads, and concentrated loads). Additionally, some cooling of the interior roof surface may occur, which will reduce the amount of radiation to the floor and reduce the cooling load.

The relative influence of removing a portion of the convective loads in the stratified zone and reducing radiation to the floor, must be related to the effect of additional make-up load.

As a rule, the minimum practical ventilation rate should be used whenever the ambient air temperature is greater than the temperature of the ventilation exhaust air.

The peak plant cooling load occurs for Case 5 during hour seventeen (5 p.m.) and for Cases 21 and 22 during hour sixteen (4 p.m.). The transient effect of reducing the interior surface roof temperature and, therefore, the radiation to the floor, are indicated by these cases.

Due to the increased make-up air load, both the peak plant cooling load and the total daily rejected cooling load increased with increases in ventilation rates. Increased ventilation rates may, however, be employed during periods of relatively low ambient air temperature to decrease the average roof temperature and increase its storage capacity in preparation for peak solar times.

TABLE 6

EFFECT OF VENTILATION RATE ON PLANT COOLING LOADS

Case No.	Ventilation Rate (% of Supply)	Time Of Peak Plant Cooling Load (Hour)	Peak Plant Cooling Load (Btu/hr-sqft)	Total Daily Rejected Cooling Load (Btu/sqft)
5	Incidental Only	17	53.3	485.5
22	20	16	57.7	514.5
21	30	16	61.0	538.3

Effect of Occupancy Pattern

In this set of cases, the effects of the internal occupancy pattern (load pattern) on plant cooling loads were investigated. Table 7 lists the computed plant cooling loads for Case 5 (ten hour load pattern), Case 17 (eighteen hour load pattern), and Case 15 (twenty-four hour load pattern). An occupancy pattern of eight hours is assumed to represent a load pattern of ten hours (add one hour before and one hour after occupancy).

For all three cases, supply air is distributed at the ten foot level. Additionally, the roof construction in all cases consisted of two inches of insulation over four inches of concrete.

There is no measurable effect of occupancy pattern on the time of occurance of peak plant cooling load.

The total daily rejected cooling load (daily cooling system energy usage) increases with increases in the duration of internal occupancy, as might be expected. However, a reduction in peak plant cooling load will occur with an increase in the duration of occupancy.

During periods of occupancy, the conditioned zone temperature was maintained in the range 75°F-78°F. Conversely, during periods of non-occupancy, the conditioned zone temperature was controlled in the range 80°F-85°F.

For all three cases investigated, the primary periods of occupancy coincide with the periods of peak solar load. However, Cases 17 and 15 also extend their periods of occupancy (periods of reduced conditioned zone temperature) into periods of low solar load. The effects of an increased duration of reduced conditioned zone temperature, during periods of low solar load, yield additional storage capacity in the roof (and floor) during periods of peak solar load.

It generally can be concluded that by maintaining a lower conditioned zone temperature during periods of low solar load, an increased thermal storage effect in the roof (and floor) during times of peak solar load will be realized.

TABLE 7

EFFECT OF OCCUPANCY PATTERN ON PLANT COOLING LOADS

Case No.	Duration Of Internal Loads (Hours)	Time Of Peak Plant Cooling Load (Hour)	Peak Plant Cooling Load (Btu/hr-sqft)	Total Daily Rejected Cooling Load (Btu/sqft)
5	10	17	53.3	485.5
17	18	17	52.4	783.2
15	24	17	50.8	1053.4

Summary of the Effects of System Variables Investigated

From the data presented and discussed in this chapter, the following conclusions may be drawn.

1. The height of the supply air inlet has a direct effect on the plant cooling load. If supply air is introduced below the roof level, allowing for stratification between the supply level and the roof, certain convective loads (e.g., lighting loads, solar loads, and other loads located in the stratified zone) will be partially isolated from the plant cooling load.

2. Although the return air duct height has a direct effect on plant cooling load, it has an almost negligible effect on the conditioned zone temperature.

3. The effects of roof construction influence not only the plant cooling loads (peak plant cooling load and total daily rejected cooling load) but also the time at which the peak plant cooling loads occur. A relatively massive, well insulated roof, compared to a low thermal mass, un-insulated roof, will not only reduce the plant cooling loads but also delay the time of occurance of the peak.

4. The height at which the light fixtures are located (in the conditioned zone or in the stratified zone) will determine to which zone the convective portion of the lighting load is contributed. If the lights, or other convective loads can be isolated in the stratified zone, only a portion of their total convective load will appear as plant cooling load.

5. Ventilation air flow rate and ventilating near the roof can reduce cooling loads if a substantial convective load is located in the stratified zone. Also, increased ventilation flow rates during non-occupancy periods can increase the storage capacity of the roof during occupied periods.

6. Although longer periods of occupancy do promote increases in the total daily rejected cooling load, there is to some extent a limited reduction in the peak plant cooling load.

7. Results indicate reductions on the order of 50% in peak load, and 40% in energy conservation, are possible.

CHAPTER VI

RECOMMENDATIONS

This program attempts to include a wide variety of factors that influence the air temperature within the structure, however, certain important elements were represented by rather gross approximations (e.g., mass flow of space air due to buoyancy effects).

Further study to determine the behavior of buoyancy driven plumes in stratified environments should be considered. Particular attention should be placed upon experimental and analytical determination of mass flows in the vicinity of convective heat sources. Additionally, the effects of conflicting flows (e.g., supply, return, and ventilation air flows) which may alter the buoyant plume flow, should be carefully examined.

Before complete confidence can be placed in results acquired from the transient computer program, full-scale verification of the computed results is needed. Comparisons with data acquired from actual full-scale experimental testing would provide the means for achieving the desired levels of confidence in the computed results.

The intent of this investigation has been to determine the transient behavior of stratified air conditioning systems in an attempt to aid in proper building design. However, in the building design process, proper determination of the design heating load and system behavior is equally as important as determination of the design cooling load. Therefore, analytical as well as experimental investigations into the cold weather (winter) behavior of stratified air conditioning systems is needed.

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APPENDIX A

LIST OF SYMBOLS

APPENDIX A

LIST OF SYMBOLS

Symbol	Significance	Units
M	Number of level of ventilation.	---
N	Number of upper level of supply.	---
K	Number of upper level in building.	---
NAIR	Number of air node adjacent to floor.	---
MRET	Number of level of return.	---
NFL	Number of floor elements.	---
KAI	Number of air node adjacent to roof.	---
q_r	Convective and radiant heat transfer at outside of roof per unit floor area.	Btu/hr-sqft
q_w	Heat transfer by transmission through the walls per unit floor area.	Btu/hr-sqft
q_{lc}	Convective portion of lighting load per unit floor area.	Btu/hr-sqft
q_{lr}	Radiant portion of lighting load per unit floor area.	Btu/hr-sqft
q_{id}	Internal disperse load per unit floor area.	Btu/hr-sqft
q_{ic}	Internal concentrated load per unit floor area.	Btu/hr-sqft
q_f	Conduction from floor to soil per unit floor area.	Btu/hr-sqft
T^+	Temperature of element at completion of desired time step.	°F
T	Temperature of element at beginning of desired time step.	°F

APPENDIX A

(Continued)

Symbol	Significance	Units
TS	Supply air temperature.	°F
TO	Outside air temperature.	°F
T_{gr}	Deep-ground temperature.	°F
SAT	Sol-air temperature.	°F
$\Delta\theta$	Size of desired computational time step.	Hour
Δx	Thickness of air element.	Feet
Δx_f	Thickness of floor element.	Feet
Δx_r	Thickness of roof element.	Feet
ρ	Density of air.	lb/cuft
ρ_f	Density of floor material.	lb/cuft
ρ_r	Density of roof material.	lb/cuft
C	Specific heat of air.	Btu/lb-°F
C_f	Specific heat of floor material.	Btu/lb-°F
C_r	Specific heat of roof material.	Btu/lb-°F
C_{tr}	Specific heat of truss material.	Btu/lb-°F
m_{tr}	Mass of truss material per unit area of floor.	lb/sqft
$\dot{m}_v$	Ventilation flow rate per unit area of floor.	lb/hr-sqft
$\dot{m}_s$	Supply flow rate per unit area of floor.	lb/hr-sqft
$\dot{m}_r$	Return flow rate per unit area of floor.	lb/hr-sqft
$\dot{m}_{re}$	Return flow rate from each element per unit area of floor.	lb/hr-sqft
$\dot{m}_{ve}$	Ventilation flow rate from each element per unit area of floor.	lb/hr-sqft

APPENDIX A

(Continued)

Symbol	Significance	Units
$\dot{m}_{se}$	Supply flow rate to each element per unit area of floor.	lb/hr-sqft
$\dot{m}_{ce}$	Circulation flow rate between elements per unit area of floor.	lb/hr-sqft
k	Thermal conductivity of air.	Btu/hr-ft-°F
k_{mix}	Macroscopic mixing coefficient.	Btu/hr-ft-°F
k_f	Thermal conductivity of floor.	Btu/hr-ft-°F
k_r	Thermal conductivity of roof.	Btu/hr-ft-°F
k_s	Thermal conductivity of soil.	Btu/hr-ft-°F
h_{ri}	Convective heat transfer coefficient for inside roof surface.	Btu/hr-sqft-°F
h_{fi}	Convective heat transfer coefficient for inside floor surface.	Btu/hr-sqft-°F
h_{ro}	Convective and radiant heat transfer coefficient for outside roof surface.	Btu/hr-sqft-°F
U_{wall}	Transmission coefficient for walls.	Btu/hr-sqft-°F
PER	Perimeter of building per unit area of floor.	ft/sqft
LOAD	Hourly internal element loads per unit area of floor.	Btu/hr-sqft
LTCLD	Hourly convective portion of element lighting load per unit area of floor.	Btu/hr-sqft
LTRLD	Hourly radiant portion of lighting load per unit area of floor.	Btu/hr-sqft
FLDLD	Distributed convective floor load per unit area of floor.	Btu/hr-sqft
σ_B	Stefan-Boltzman constant.	Btu/hr-sqft-°R^4
SF	Floor surface density factor.	---

APPENDIX A

(Continued)

Symbol	Significance	Units
ε_1	Emissivity of floor.	---
ε_1	Emissivity of roof.	---

APPENDIX B

DETAILED DESCRIPTION OF TRANSIENT CASES INVESTIGATED

CASE 3

Roof Height (Feet)	Supply Height (Feet)	Return Height (Feet)	Ventilation Height (Feet)	Lighting Height (Feet)
20.0	20.0	1.0	19.0	18.0

Name Of Roof Material	Thickness (Feet)	Name Of Floor Material	Thickness (Feet)
Roof Insulation	0.17	Floor Slab	0.33
Built Up Roofing	0.33	Soil	5.00

Solar Time (Hour)	Supply Temp. (°F)	Supply Rate (cfm/sqft)	Return Rate (cfm/sqft)	Lighting Load (Btu/hr-sqft)	Internal Disperse Loads (Btu/hr-sqft)
1	76.0	1.2	1.1		
2	76.0	1.2	1.1		
3	75.0	1.2	1.1		
4	74.0	1.2	1.1		
5	74.0	1.2	1.1		
6	74.0	1.2	1.1		
7	75.0	1.2	1.1		
8	55.0	1.8	1.7	8.0	30.0
9	55.0	1.9	1.8	8.0	30.0
10	55.0	1.9	1.8	8.0	30.0
11	55.0	2.2	2.1	8.0	30.0
12	55.0	2.4	2.3	8.0	30.0
13	55.0	2.9	2.8	8.0	30.0
14	55.0	3.0	2.9	8.0	30.0
15	55.0	3.1	3.0	8.0	30.0
16	55.0	3.4	3.3	8.0	30.0
17	55.0	3.7	3.6	8.0	30.0
18	55.0	1.1	1.0		
19	55.0	0.8	0.7		
20	55.0	0.6	0.5		
21	55.0	0.5	0.4		
22	55.0	0.5	0.4		
23	79.0	1.2	1.1		
24	77.0	1.2			

CASE 4

Roof Height (Feet)	Supply Height (Feet)	Return Height (Feet)	Ventilation Height (Feet)	Lighting Height (Feet)
20.0	10.0	1.0	19.0	12.0

Name Of Roof Material	Thickness (Feet)	Name Of Floor Material	Thickness (Feet)
Roof Insulation	0.17	Floor Slab	0.33
Steel Roof Decking	0.02	Soil	5.00

Solar Time (Hour)	Supply Temp. (°F)	Supply Rate (cfm/sqft)	Return Rate (cfm/sqft)	Lighting Load (Btu/hr-sqft)	Internal Disperse Loads (Btu/hr-sqft)
1	76.0	1.2	1.1		
2	76.0	1.2	1.1		
3	75.0	1.2	1.1		
4	74.0	1.2	1.1		
5	74.0	1.2	1.1		
6	74.0	1.2	1.1		
7	75.0	1.2	1.0		
8	55.0	1.4	1.3	8.0	30.0
9	55.0	1.4	1.3	8.0	30.0
10	55.0	1.4	1.3	8.0	30.0
11	55.0	1.7	1.6	8.0	30.0
12	55.0	1.7	1.6	8.0	30.0
13	55.0	2.0	1.9	8.0	30.0
14	55.0	2.0	1.9	8.0	30.0
15	55.0	2.0	1.9	8.0	30.0
16	55.0	2.1	2.0	8.0	30.0
17	55.0	2.1	2.0	8.0	30.0
18	55.0	0.6	0.5		
19	55.0	0.6	0.5		
20	55.0	0.3	0.2		
21	55.0	0.3	0.2		
22	81.0	1.2	1.1		
23	79.0	1.2	1.1		
24	77.0	1.2	1.1		

CASE 5

Roof Height (Feet)	Supply Height (Feet)	Return Height (Feet)	Ventilation Height (Feet)	Lighting Height (Feet)
20.0	10.0	1.0	19.0	12.0

Name Of Roof Material	Thickness (Feet)	Name Of Floor Material	Thickness (Feet)
Roof Insulation	0.17	Floor Slab	0.33
Built Up Roofing	0.33	Soil	5.00

Solar Time (Hour)	Supply Temp. (°F)	Supply Rate (cfm/sqft)	Return Rate (cfm/sqft)	Lighting Load (Btu/hr-sqft)	Internal Disperse Loads (Btu/hr-sqft)
1	76.0	1.2	1.1		
2	76.0	1.2	1.1		
3	75.0	1.2	1.1		
4	74.0	1.2	1.1		
5	74.0	1.2	1.1		
6	74.0	1.2	1.1		
7	75.0	1.2	1.1		
8	55.0	1.4	1.3	8.0	30.0
9	55.0	1.4	1.3	8.0	30.0
10	55.0	1.4	1.3	8.0	30.0
11	55.0	1.7	1.6	8.0	30.0
12	55.0	1.7	1.6	8.0	30.0
13	55.0	2.0	1.9	8.0	30.0
14	55.0	2.0	1.9	8.0	30.0
15	55.0	2.0	1.9	8.0	30.0
16	55.0	2.1	2.0	8.0	30.0
17	55.0	2.1	2.0	8.0	30.0
18	55.0	0.6	0.5		
19	55.0	0.6	0.5		
20	55.0	0.3	0.2		
21	55.0	0.3	1.2		
22	81.0	1.2	1.1		
23	79.0	1.2	1.1		
24	77.0	1.2	1.1		

CASE 6

Roof Height (Feet)	Supply Height (Feet)	Return Height (Feet)	Ventilation Height (Feet)	Lighting Height (Feet)
20.0	10.0	5.0	19.0	12.0

Name Of Roof Material	Thickness (Feet)	Name Of Floor Material	Thickness (Feet)
Roof Insulation	0.17	Floor Slab	0.33
Built Up Roofing	0.33	Soil	5.0

Solar Time (Hour)	Supply Temp. (°F)	Supply Rate (cfm/sqft)	Return Rate (cfm/sqft)	Lighting Load (Btu/hr-sqft)	Internal Disperse Loads (Btu/hr-sqft)
1	76.0	1.2	1.1		
2	76.0	1.2	1.1		
3	75.0	1.2	1.1		
4	74.0	1.2	1.1		
5	74.0	1.2	1.1		
6	74.0	1.2	1.1		
7	75.0	1.2	1.1		
8	55.0	1.4	1.3	8.0	30.0
9	55.0	1.5	1.4	8.0	30.0
10	55.0	1.6	1.5	8.0	30.0
11	55.0	1.8	1.7	8.0	30.0
12	55.0	1.8	1.7	8.0	30.0
13	55.0	2.1	2.0	8.0	30.0
14	55.0	2.1	2.0	8.0	30.0
15	55.0	2.1	2.0	8.0	30.0
16	55.0	2.2	2.1	8.0	30.0
17	55.0	2.2	2.1	8.0	30.0
18	55.0	0.8	0.7		
19	55.0	0.7	0.6		
20	55.0	0.3	0.2		
21	55.0	0.3	0.2		
22	81.0	1.2	1.1		
23	79.0	1.2	1.1		
24	77.0	1.2	1.1		

CASE 7

Roof Height (Feet)	Supply Height (Feet)	Return Height (Feet)	Ventilation Height (Feet)	Lighting Height (Feet)
20.0	10.0	19.0	19.0	12.0

Name Of Roof Material	Thickness (Feet)	Name Of Floor Material	Thickness (Feet)
Roof Insulation	0.17	Floor Slab	0.33
Built Up Roofing	0.33	Soil	5.00

Solar Time (Hour)	Supply Temp. (°F)	Supply Rate (cfm/sqft)	Return Rate (cfm/sqft)	Lighting Load (Btu/hr-sqft)	Internal Disperse Loads (Btu/hr-sqft)
1	76.0	1.2	1.1		
2	76.0	1.2	1.1		
3	75.0	1.2	1.1		
4	74.0	1.2	1.1		
5	74.0	1.2	1.1		
6	74.0	1.2	1.1		
7	75.0	1.2	1.1		
8	55.0	1.4	1.3	8.0	30.0
9	55.0	1.5	1.4	8.0	30.0
10	55.0	1.6	1.5	8.0	30.0
11	55.0	1.8	1.7	8.0	30.0
12	55.0	1.8	1.7	8.0	30.0
13	55.0	2.1	2.0	8.0	30.0
14	55.0	2.1	2.0	8.0	30.0
15	55.0	2.1	2.0	8.0	30.0
16	55.0	2.2	2.1	8.0	30.0
17	55.0	2.2	2.1	8.0	30.0
18	55.0	0.8	0.7		
19	55.0	0.7	0.6		
20	55.0	0.3	0.2		
21	55.0	0.3	0.2		
22	81.0	1.2	1.1		
23	79.0	1.2	1.1		
24	77.0	1.2	1.1		

CASE 8

Roof Height (Feet)	Supply Height (Feet)	Return Height (Feet)	Ventilation Height (Feet)	Lighting Height (Feet)
20.0	10.0	1.0	19.0	12.0

Name Of Roof Material	Thickness (Feet)	Name Of Floor Material	Thickness (Feet)
Roof Insulation	0.17	Floor Slab	0.33
Built Up Roofing	0.75	Soil	5.00

Solar Time (Hour)	Supply Temp. (°F)	Supply Rate (cfm/sqft)	Return Rate (cfm/sqft)	Lighting Load (Btu/hr-sqft)	Internal Disperse Loads (Btu/hr-sqft)
1	76.0	1.2	1.1		
2	76.0	1.2	1.1		
3	75.0	1.2	1.1		
4	74.0	1.2	1.1		
5	74.0	1.2	1.1		
6	74.0	1.2	1.1		
7	75.0	1.2	1.1		
8	55.0	1.4	1.3	8.0	30.0
9	55.0	1.5	1.4	8.0	30.0
10	55.0	1.6	1.5	8.0	30.0
11	55.0	1.8	1.7	8.0	30.0
12	55.0	1.8	1.7	8.0	30.0
13	55.0	2.1	2.0	8.0	30.0
14	55.0	2.1	2.0	8.0	30.0
15	55.0	2.1	2.0	8.0	30.0
16	55.0	2.2	2.1	8.0	30.0
17	55.0	2.2	2.1	8.0	30.0
18	55.0	0.8	0.7		
19	55.0	0.7	0.6		
20	55.0	0.3	0.2		
21	55.0	0.3	0.2		
22	81.0	1.2	1.1		
23	79.0	1.2	1.1		
24	77.0	1.2	1.1		

CASE 10

Roof Height (Feet)	Supply Height (Feet)	Return Height (Feet)	Ventilation Height (Feet)	Lighting Height (Feet)
20.0	18.0	1.0	19.0	12.0

Name Of Roof Material	Thickness (Feet)	Name Of Floor Material	Thickness (Feet)
Roof Insulation	0.17	Floor Slab	0.33
Built Up Roofing	0.33	Soil	5.00

Solar Time (Hour)	Supply Temp. (°F)	Supply Rate (cfm/sqft)	Return Rate (cfm/sqft)	Lighting Load (Btu/hr-sqft)	Internal Disperse Loads (Btu/hr-sqft)
1	76.0	1.2	1.1		
2	76.0	1.2	1.1		
3	75.0	1.2	1.1		
4	74.0	1.2	1.1		
5	74.0	1.2	1.1		
6	74.0	1.2	1.1		
7	75.0	1.2	1.1		
8	55.0	1.4	1.3	8.0	30.0
9	55.0	1.4	1.3	8.0	30.0
10	55.0	1.5	1.4	8.0	30.0
11	55.0	1.8	1.7	8.0	30.0
12	55.0	1.8	1.7	8.0	30.0
13	55.0	2.1	2.0	8.0	30.0
14	55.0	2.1	2.0	8.0	30.0
15	55.0	2.1	2.0	8.0	30.0
16	55.0	2.2	2.1	8.0	30.0
17	55.0	2.2	2.1	8.0	30.0
18	55.0	0.6	0.5		
19	55.0	0.6	0.5		
20	55.0	0.3	0.2		
21	55.0	0.3	0.2		
22	81.0	1.2	1.1		
23	79.0	1.2	1.1		
24	77.0	1.2	1.1		

CASE 15

Roof Height (Feet)	Supply Height (Feet)	Return Height (Feet)	Ventilation Height (Feet)	Lighting Height (Feet)
20.0	10.0	1.0	19.0	12.0

Name Of Roof Material	Thickness (Feet)	Name Of Floor Material	Thickness (Feet)
Roof Insulation	0.17	Floor Slab	0.33
Built Up Roofing	0.33	Soil	5.00

Solar Time (Hour)	Supply Temp. (°F)	Supply Rate (cfm/sqft)	Return Rate (cfm/sqft)	Lighting Load (Btu/hr-sqft)	Internal Disperse Load (Btu/hr-sqft)
1	55.0	2.0	1.9	8.0	30.0
2	55.0	2.0	1.9	8.0	30.0
3	55.0	2.0	1.9	8.0	30.0
4	55.0	2.0	1.9	8.0	30.0
5	55.0	2.0	1.9	8.0	30.0
6	55.0	2.0	1.9	8.0	30.0
7	55.0	2.0	1.9	8.0	30.0
8	55.0	2.0	1.9	8.0	30.0
9	55.0	2.0	1.9	8.0	30.0
10	55.0	2.0	1.9	8.0	30.0
11	55.0	2.0	1.9	8.0	30.0
12	55.0	2.0	1.9	8.0	30.0
13	55.0	2.0	1.9	8.0	30.0
14	55.0	2.0	1.9	8.0	30.0
15	55.0	2.0	1.9	8.0	30.0
16	55.0	2.0	1.9	8.0	30.0
17	55.0	2.0	1.9	8.0	30.0
18	55.0	2.0	1.9	8.0	30.0
19	55.0	2.0	1.9	8.0	30.0
20	55.0	2.0	1.9	8.0	30.0
21	55.0	2.0	1.9	8.0	30.0
22	55.0	2.0	1.9	8.0	30.0
23	55.0	2.0	1.9	8.0	30.0
24	55.0	2.0	1.9	8.0	30.0

CASE 17

Roof Height (Feet)	Supply Height (Feet)	Return Height (Feet)	Ventilation Height (Feet)	Lighting Height (Feet)
20.0	10.0	1.0	19.0	12.0

Name Of Roof Material	Thickness (Feet)	Name Of Floor Material	Thickness (Feet)
Roof Insulation	0.17	Floor Slab	0.33
Built Up Roofing	0.33	Soil	5.00

Solar Time (Hour)	Supply Temp. (°F)	Supply Rate (cfm/sqft)	Return Rate (cfm/sqft)	Lighting Load (Btu/hr-sqft)	Internal Disperse Loads (Btu/hr-sqft)
1	76.0	1.2	1.1		
2	76.0	1.2	1.1		
3	75.0	1.2	1.1		
4	74.0	1.2	1.1		
5	74.0	1.2	1.1		
6	74.0	1.2	1.1		
7	75.0	1.2	1.1		
8	55.0	1.4	1.3	8.0	30.0
9	55.0	1.4	1.3	8.0	30.0
10	55.0	1.4	1.3	8.0	30.0
11	55.0	1.6	1.5	8.0	30.0
12	55.0	1.7	1.6	8.0	30.0
13	55.0	2.0	1.9	8.0	30.0
14	55.0	2.0	1.9	8.0	30.0
15	55.0	2.0	1.9	8.0	30.0
16	55.0	2.0	1.9	8.0	30.0
17	55.0	2.0	1.9	8.0	30.0
18	55.0	2.0	1.9	8.0	30.0
19	55.0	1.9	1.8	8.0	30.0
20	55.0	1.9	1.8	8.0	30.0
21	55.0	1.7	1.6	8.0	30.0
22	55.0	1.7	1.6	8.0	30.0
23	55.0	1.5	1.4	8.0	30.0
24	55.0	1.5	1.4	8.0	30.0

CASE 19

Roof Height (Feet)	Supply Height (Feet)	Return Height (Feet)	Ventilation Height (Feet)	Lighting Height (Feet)
20.0	10.0	1.0	19.0	10.0

Name Of Roof Material	Thickness (Feet)	Name Of Floor Material	Thickness (Feet)
Roof Insulation	0.17	Floor Slab	0.33
Built Up Roofing	0.33	Soil	5.00

Solar Time (Hour)	Supply Temp. (°F)	Supply Rate (cfm/sqft)	Return Rate (cfm/sqft)	Lighting Load (Btu/hr-sqft)	Internal Disperse Loads (Btu/hr-sqft)
1	76.0	1.2	1.1		
2	76.0	1.2	1.1		
3	75.0	1.2	1.1		
4	74.0	1.2	1.1		
5	74.0	1.2	1.1		
6	74.0	1.2	1.1		
7	75.0	1.2	1.1		
8	55.0	1.4	1.3	8.0	30.0
9	55.0	1.5	1.4	8.0	30.0
10	55.0	1.6	1.5	8.0	30.0
11	55.0	1.8	1.7	8.0	30.0
12	55.0	1.8	1.7	8.0	30.0
13	55.0	2.2	2.1	8.0	30.0
14	55.0	2.2	2.1	8.0	30.0
15	55.0	2.2	2.1	8.0	30.0
16	55.0	2.3	2.2	8.0	30.0
17	55.0	2.3	2.2	8.0	30.0
18	55.0	1.0	0.9		
19	55.0	1.0	0.9		
20	55.0	0.6	0.5		
21	55.0	0.6	0.5		
22	81.0	1.2	1.1		
23	79.0	1.2	1.1		
24	77.0	1.2	1.1		

CASE 20

Roof Height (Feet)	Supply Height (Feet)	Return Height (Feet)	Ventilation Height (Feet)	Lighting Height (Feet)
20.0	10.0	1.0	12.0	12.0

Name Of Roof Material	Thickness (Feet)	Name Of Floor Material	Thickness (Feet)
Roof Insulation	0.17	Floor Slab	0.33
Built Up Roofing	0.33	Soil	5.00

Solar Time (Hour)	Supply Temp. (°F)	Supply Rate (cfm/sqft)	Return Rate (cfm/sqft)	Lighting Load (Btu/hr-sqft)	Internal Disperse Loads (Btu/hr-sqft)
1	76.0	1.2	1.1		
2	76.0	1.2	1.1		
3	75.0	1.2	1.1		
4	74.0	1.2	1.1		
5	74.0	1.2	1.1		
6	74.0	1.2	1.1		
7	75.0	1.2	1.1		
8	55.0	1.4	1.3	8.0	30.0
9	55.0	1.5	1.4	8.0	30.0
10	55.0	1.6	1.5	8.0	30.0
11	55.0	1.8	1.7	8.0	30.0
12	55.0	1.8	1.7	8.0	30.0
13	55.0	2.2	2.1	8.0	30.0
14	55.0	2.2	2.1	8.0	30.0
15	55.0	2.2	2.1	8.0	30.0
16	55.0	2.3	2.2	8.0	30.0
17	55.0	2.3	2.2	8.0	30.0
18	55.0	1.0	0.9		
19	55.0	1.0	0.9		
20	55.0	0.6	0.5		
21	55.0	0.6	0.5		
22	81.0	1.2	1.1		
23	79.0	1.2	1.1		
24	77.0	1.2	1.1		

CASE 21

Roof Height (Feet)	Supply Height (Feet)	Return Height (Feet)	Ventilation Height (Feet)	Lighting Height (Feet)
20.0	10.0	1.0	19.0	12.0

Name Of Roof Material	Thickness (Feet)	Name Of Floor Material	Thickness (Feet)
Roof Insulation	0.17	Floor Slab	0.33
Built Up Roofing	0.33	Soil	5.00

Solar Time (Hour)	Supply Temp. (°F)	Supply Rate (cfm/sqft)	Return Rate (cfm/sqft)	Lighting Load (Btu/hr-sqft)	Internal Disperse Loads (Btu/hr-sqft)
1	76.0	1.2	0.8		
2	76.0	1.2	0.8		
3	75.0	1.2	0.8		
4	74.0	1.2	0.8		
5	74.0	1.2	0.8		
6	74.0	1.2	0.8		
7	75.0	1.2	0.8		
8	55.0	1.4	1.0	8.0	30.0
9	55.0	1.4	1.0	8.0	30.0
10	55.0	1.4	1.0	8.0	30.0
11	55.0	1.7	1.2	8.0	30.0
12	55.0	1.7	1.2	8.0	30.0
13	55.0	2.0	1.4	8.0	30.0
14	55.0	2.0	1.4	8.0	30.0
15	55.0	2.0	1.4	8.0	30.0
16	55.0	2.1	1.5	8.0	30.0
17	55.0	2.1	1.5	8.0	30.0
18	55.0	0.6	0.4		
19	55.0	0.6	0.4		
20	55.0	0.3	0.2		
21	55.0	0.3	0.2		
22	81.0	1.2	0.8		
23	79.0	1.2	0.8		
24	77.0	1.2	0.8		

CASE 22

Roof Height (Feet)	Supply Height (Feet)	Return Height (Feet)	Ventilation Height (Feet)	Lighting Height (Feet)
20.0	10.0	1.0	19.0	12.0

Name Of Roof Material	Thickness (Feet)	Name Of Floor Material	Thickness (Feet)
Roof Insulation	0.17	Floor Slab	0.33
Built Up Roofing	0.33	Soil	5.00

Solar Time (Hour)	Supply Temp. (°F)	Supply Rate (cfm/sqft)	Return Rate (cfm/sqft)	Lighting Load (Btu/hr-sqft)	Internal Disperse Loads (Btu/hr-sqft)
1	76.0	1.2	1.0		
2	76.0	1.2	1.0		
3	75.0	1.2	1.0		
4	74.0	1.2	1.0		
5	74.0	1.2	1.0		
6	74.0	1.2	1.0		
7	75.0	1.2	1.0		
8	55.0	1.4	1.1	8.0	30.0
9	55.0	1.4	1.1	8.0	30.0
10	55.0	1.4	1.1	8.0	30.0
11	55.0	1.7	1.4	8.0	30.0
12	55.0	1.7	1.4	8.0	30.0
13	55.0	2.0	1.6	8.0	30.0
14	55.0	2.0	1.6	8.0	30.0
15	55.0	2.0	1.6	8.0	30.0
16	55.0	2.1	1.7	8.0	30.0
17	55.0	2.1	1.7	8.0	30.0
18	55.0	0.6	0.5		
19	55.0	0.6	0.5		
20	55.0	0.3	0.2		
21	55.0	0.3	0.2		
22	81.0	1.2	1.0		
23	79.0	1.2	1.0		
24	77.0	1.2	1.0		

CASE 25

Roof Height (Feet)	Supply Height (Feet)	Return Height (Feet)	Ventilation Height (Feet)	Lighting Height (Feet)
20.0	10.0	1.0	19.0	12.0

Name Of Roof Material	Thickness (Feet)	Name Of Floor Material	Thickness (Feet)
Steel Roof Decking	0.02	Floor Slab	0.33
		Soil	5.00

Solar Time (Hour)	Supply Temp. (°F)	Supply Rate (cfm/sqft)	Return Rate (cfm/sqft)	Lighting Load (Btu/hr-sqft)	Internal Disperse Loads (Btu/hr-sqft)
1	76.0	1.2	1.1		
2	76.0	1.2	1.1		
3	75.0	1.2	1.1		
4	74.0	1.2	1.1		
5	74.0	1.2	1.1		
6	74.0	1.2	1.1		
7	75.0	1.2	1.1		
8	55.0	1.6	1.5	8.0	30.0
9	55.0	1.6	1.5	8.0	30.0
10	55.0	1.8	1.7	8.0	30.0
11	55.0	2.0	1.9	8.0	30.0
12	55.0	2.0	1.9	8.0	30.0
13	55.0	2.6	2.5	8.0	30.0
14	55.0	2.6	2.5	8.0	30.0
15	55.0	2.7	2.6	8.0	30.0
16	55.0	2.8	2.7	8.0	30.0
17	55.0	2.8	2.7	8.0	30.0
18	55.0	1.5	1.4		
19	55.0	1.5	1.4		
20	55.0	1.0	0.9		
21	55.0	1.0	0.9		
22	81.0	1.2	1.1		
23	79.0	1.2	1.1		
24	77.0	1.2	1.1		

APPENDIX C

LISTING OF THE COMPUTER PROGRAM USING THE FORTRAN LANGUAGE

FILE: TRANS FORTRAN A1 KANSAS STATE UNIVERSITY VM/SP CMS

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C
C SIMULATION OF THE TRANSIENT BEHAVIOR OF
C STRATIFIED AIR CONDITIONING SYSTEMS
C
C
C   NOTE: FOUR AIR NODES SHOULD BE CONSIDERED THE MINIMUM
C         PRACTICAL NUMBER
C
C
C HSAT= HOURLY SOL-AIR TEMPERATURE (DEG F)
C HTS=HOURLY SUPPLY AIR TEMPERATURE (DEG F)
C HTO=HOURLY OUTSIDE AIR TEMPERATURE (CEG F)
C HSUP=HOURLY SUPPLY AIR FLOWRATE (CFM/SQFT)
C HRET=HOURLY RETURN AIR FLOWRATE (CFM/SQFT)
C HLTS=HOURLY LIGHTING LOAD IN BUILDING (BTU/HR SQFT)
C HLOAD=HOURLY INTERNAL LOAD FOR EACH ELEMENT(BTU/HR SQFT)
C
C SOLLD=SOLAR AND CONVECTIVE LOAD ON OUTSIDE OF ROOF (BTU/HR SQFT)
C RFCLD= CCNVECTIVE ROOF LOAD INTO SPACE (BTU/HR SQFT)
C RFRLD=NET RADIANT ROOF LOAD CNTO FLOOR OR ROOF (BTU/HR SQFT)
C FLCLD=CONVECTIVE FLOOR LOAD INTO SPACE (BTU/HR SQFT)
C WALCLD=CONVECTIVE WALL LOAD INTO SPACE (INSTANTANEOUS) (BTU/HR SQFT)
C LTCLD=CONVECTIVE PORTION OF LIGHTING LOAD (BTU/HR SQFT)
C LTRLD=RADIANT PORTION OF LIGHTING LOAD (BTU/HR SQFT)
C VENTLD=VENTILATION PORTION OF SPACE LOAD (BTU/HR SQFT)
C RETLD=RETURN AIR PORTION OF SPACE LOAD (BTU/HR SQFT)
C
C HRO=OUTSIDE ROOF FILM COEFFICIENT (BTU/HR SQFT DEGF)
C HRI=INSIDE ROOF FILM COEFFICIENT (BTU/HR SQFT DEGF)
C HFI=INSIDE FLOOR FILM COEFFICIENT (BTU/HR SQFT DEGF)
C
C MSE=SUPPLY TO INDIVIDUAL ELEMENT(LB/HR SQFT)
C MRE=RETURN FROM INDIVIDUAL ELEMENT(LB/HR SQFT)
C MVE=VENTILATION FROM INDIVIDUAL ELEMENT(LB/HR SQFT)
C MCE=CIRCULATION BETWEEN ELEMENTS (LB/HR SQFT)
C MS=SUPPLY AIR FLOW TO ENTIRE BUILDING (LB/HR SQFT)
C MV=VENTILATION AIR FLOW FROM ENTIRE BUILDING (LB/HR SQFT)
C MR=RETURN AIR FLOW FROM ENTIRE BUILDING (LB/HR SQFT)
C
C PER=PERIMETER OF BUILDING PER SQUARE FOOT OF FLCOR SPACE (FT/SQ FT)
C TRMASS=MASS CF ROOF TRUSSES (LB/SQ FT)
C CPSTL=SPECIFIC HEAT OF ROOF TRUSS MATERIAL (BTU/LB DEGF)
C SF=RADIATION SHAPE FACTOR
C
C M=NO OF LEVEL OF VENTILATION
C N=NO OF LEVEL OF SUPPLY
C K=NO OF UPPER LEVEL IN BUILDING
C MRET=NO CF LEVEL OF RETURN
C NLTS=NO OF LEVEL OF LIGHTS
C NROOF=NUMBER OF RCOF MATERIALS
C NFLOOR=NUMBER OF FLOOR AND SOIL MATERIALS
C NN=NUMBER OF ROOF TEMPERATURE NODES
C NFL=NUMBER OF FLOOR TEMPERATURE NODES
C II=TOTAL NUMBER OF TEMPERATURE NODES IN MODEL
C NAIR=FIRST AIR NODE
C KAI=UPPER AIR NODE
C
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```
    7 FORMAT (18A4)
    8 FORMAT (I2,2(3X,I2),8X,F10.2)
    9 FORMAT (5A4,4F10.4)
   11 FORMAT (12F6.2)
   15 FORMAT (I2,4(3X,I2))
   16 FORMAT (2F10.2,5F10.4)
   18 FORMAT (' ',T15,'NAME OF FLOOR',T34,'THICKNESS'
     +,T70,'CONDUCTIVITY',T90,'DENSITY',T106,'HEAT')
   20 FORMAT ('0',40X,'HOURLY LOADS FOR DAY',2X,I2)
   21 FORMAT ('0',6X,'SOLLD',T20,'RFCLD',T32,'RFRLD',T44,'RFST',T56,
     +'FLCLD',T68,'WALCLD',T80,'LTLD',T92,'EXLD',T104,'RETLD',T116,
     +'MUALD')
   22 FORMAT (' ',1X,'TIME',10(1X,'BTU/HR-SQFT'))
   23 FORMAT (' ',1X,'____',10(1X,'___________'))
   24 FORMAT ('0',2X,I2,1X,10(1X,F11.3))
   30 FORMAT ('-',T5,'MASS OF ROOF TRUSSES',T30,
     +'SPECIFIC HEAT OF TRUSS MATERIAL',T80,'RADIATION SHAPE FACTOR')
   31 FORMAT (' ',T10,'(LB/SQFT)',T35,'(BTU/LB DEGF)')
   32 FORMAT ('0',T10,F10.4,T35,F10.4,T88,F10.4)
   39 FORMAT ('1',30X,18A4)
   40 FORMAT ('-',5X,60('* '))
   41 FORMAT ('0',5X,60('* '))
   42 FORMAT ('0',52X,'GENERAL PROGRAM VARIABLES:')
   43 FORMAT ('-',10X,'SPECIFIC HEAT',T34,'DENSITY OF',T50,
     +'THERMAL CONDUCTIVITY',T80,'MIXING',T100,'INITIAL',T116,
     +'SIZE OF')
   44 FORMAT (' ',12X,'OF AIR',T38,'AIR',T56,'OF AIR',T78,
     +'COEFFICIENT',T99,'TEMPERATURE',T115,'TIME STEP')
   45 FORMAT (' ',9X,'(BTU/LB DEGF)',T34,'(LB/CUFT)',T53,
     +'(BTU/HR FT DEGF)',T76,'(BTU/HR FT DEGF)',T101,
     +'(DEGF)',T118,'(HR)')
   48 FORMAT ('-',T12,'TOTAL NUMBER OF',T36,'NUMBER OF LAYERS',T58,
     +'NUMBER OF LAYER',T78,'NUMBER OF LAYER',T98,'NUMBER OF LAYER')
   49 FORMAT (' ',T10,'LAYERS IN BUILDING',T36,'WITH SUPPLY',T60,
     +'WITH VENT',T78,'WITH RETURN',T98,'WITH LIGHTS')
   50 FORMAT ('-',T20,'PERIMETER OF',T40,'FLOOR AREA OF',T61,
     +'OVERALL H.T. COEFFICIENT',T90,'THICKNESS OF')
   51 FORMAT (' ',T22,'BUILDING',T43,'BUILDING',T67,'OF WALLS',T92,
     +'AIR LAYER')
   52 FORMAT (' ',T24,'(FT)',T44,'(SQFT)',T63,'(BTU/HR SQFT DEGF)',T95,
     +'(FT)')
   53 FORMAT ('-',T72,'THERMAL',T104,
     +'SPECIFIC')
   54 FORMAT (' ',T15,'NAME OF ROOF',T34,'THICKNESS'
     +,T70,'CONDUCTIVITY',T90,'DENSITY',T106,'HEAT')
   55 FORMAT (' ',T17,'MATERIAL',T37,'(FT)',
     +T68,'(BTU/HR FT DEGF)',T89,'(LB/CUFT)',T102,'(BTU/LB DEGF)')
   60 FORMAT ('0',T30,'ELEMENT',T80,'TEMPERATURE PROFILE')
   61 FORMAT (' ',T30,'HEAT LOADS',T84,'OF AIR')
   62 FORMAT (' ',T30,'(BTU/HR SQFT)',T84,'(DEGF)')
   74 FORMAT (' ',T30,F10.2,T80,F10.2)
   75 FORMAT (' ',T80,F10.2)
   80 FORMAT ('0',10X,F10.4,11X,F10.4,11X,F10.4,15X,
     +F10.4,10X,F10.1,5X,F10.4)
   81 FORMAT ('0',T16,I2,T40,I2,T62,I2,T82,I2,T102,I2)
   82 FORMAT ('0',T20,F8.2,T40,F10.2,T65,F8.4,T91,F8.1)
   83 FORMAT ('0',T10,5A4,T31,F10.2,T71,F10.2,T88,
```

```
     +F10.2,T103,F10.4)
  84 FORMAT ('-',T5,'SOL-AIR TEMP.',T25,'OUTSIDE AIR TEMP.',T46,
     +'SUPPLY AIR TEMP.',T67,'SUPPLY RATE',T85,'RETURN RATE',T100,
     +'VENT RATE')
  85 FORMAT (' ',T10,'(DEGF)',T30,'(DEGF)',T51,'(DEGF)',T67,'(CFM/SQFT)
     +',T85,'(CFM/SQFT)',T100,'(CFM/SQFT)')
  86 FORMAT (' ',T10,'______',T30,'______',T51,'______',T67,
     +'___________',T85,'___________',T100,'___________')
  87 FORMAT ('0',T5,F10.2,T25,F10.2,T46,F10.2,T67,F10.2,T85,F10.2,
     +T100,F10.2)
  88 FORMAT ('0',T30,'HOURLY AIR TEMPERATURES AND FLOWS FOR DAY ',I2)
  89 FORMAT ('0',T55,'SUMMATION FOR HOUR ',I2)
      REAL MSE(15),MVE(15),MRE(15),MCE(15),KAIR,KMIX,KRF(2),LOAD(15)
      REAL LTRLD,LTCLD(15),D5(15)
      REAL MS,MR,MV,RFRLD,KFL(2)
      DIMENSION A(25,26),T(25),YY(25)
      DIMENSION RHOFL(2),CPFL(2),DELXFL(2),FLNAME(5,2),THFL(2)
      DIMENSION RHORF(2),CPRF(2),DELXX(2),RNAME(5,2),THRF(2)
      DIMENSION HLOAD(15,24),HLTS(24),HSAT(24),HTO(24),HTS(24)
      DIMENSION HSUP(24),HRET(24),HVENT(24)
      DIMENSION DESCR(18),SOLD(7,24),SRFCLD(7,24),SRFRLD(7,24)
      DIMENSION SRFST(7,24),SFLCLD(7,24),SWALCL(7,24),SLTLD(7,24)
      DIMENSION SEXLD(7,24),SRETLD(7,24),SVENLD(7,24)
C
C DEFINE GENERAL PROGRAM VARIABLES
C
      TI=80.
C **************************************
C
C THE INITIAL FLOOR TEMPERATURE SHOULD BE SET AT 55 DEG F FOR ALL
C ACTUAL RUNS--DURING TESTING SET TO DESIRED VALUE
C
      TFI=55.
C
C **************************************
      CPAIR=.24
      RHOAIR=.075
      KAIR=.015
      KMIX=0.075
      PERRLT=.80
      EPS1=.80
      EPS2=.80
      SIGMA=.1714E-08
C
C READ CASE DESCRIPTION
C
      READ (5,7) DESCR
C
C READ TIME STEP VARIABLES
C
      READ (5,8) ND,NHO,NSTP,THETA
C
C READ FLOOR MATERIALS
C
      READ (5,8) NFLOOR
      DO 100 I=1,NFLOOR
      READ(5,9) (FLNAME(J,I),J=1,5),KFL(I),RHOFL(I),CPFL(I),THFL(I)
```

```
  100 CONTINUE
C
C READ ROOF MATERIALS
C
      READ (5,9) NROOF
      DO 110 I=1,NROOF
      READ(5,9) (RNAME(J,I),J=1,5),KRF(I),RHORF(I),CPRF(I),THRF(I)
  110 CONTINUE
C
C READ BUILDING VARIABLES
C
      READ(5,15) K,N,M,MRET,NLTS
      READ(5,16) DELX,AREA,PER,UWALL,TRMASS,CPSTL,SF
C ************************************
C
C THE NEXT TWO LINES ARE JUST USED WHEN COMPARING TO THE STEADY STATE
C MODEL-- COMMENT THEM OUT IN ACTUAL RUNS
C     READ (5,10) QROOF,QFLOOR
C  10 FORMAT (2F10.4)
C
C ************************************
C
C READ HOURLY HEAT LOADS, TEMPERATURES AND FLOWRATES
C
      READ (5,11) (HSAT(I),I=1,24)
      READ (5,11) (HTS(I),I=1,24)
      READ (5,11) (HTO(I),I=1,24)
      READ (5,11) (HSUP(I),I=1,24)
      READ (5,11) (HRET(I),I=1,24)
      READ (5,11) (HLTS(I),I=1,24)
      DO 120 JJ=1,K
      READ (5,11) (HLOAD(JJ,I),I=1,24)
  120 CONTINUE
C
C
C
C
C SET ALL ELEMENT FLOWRATES AND LOADS TO ZERO AND INITIALIZE
C ALL ELEMENT TEMPERATURES
C
      DO 200 I=1,K
      MSE(I)=0.0
      MRE(I)=0.0
      MVE(I)=0.0
      MCE(I)=0.0
  200 CONTINUE
C
C INITIALIZE FLOOR TEMPERATURES
C
      NFL=NFLOOR*2.+1
      NFL1=NFL+1
      DO 205 I=1,NFL
      T(I)=TFI
  205 CONTINUE
C
      NN=2*NROOF+1
      II=K+NFL+NN
```

```
      II1=II+1
      NAIR=NFL+1
      KAI=NFL+K
      NAIR1=NAIR+1
      KAM1=KAI-1
C
C INITIALIZE ROOF AND AIR TEMPERATURES
C
      DO 210 I=NFL1,II
      T(I)=TI
  210 CONTINUE
C
C
C CALCULATE THE THERMAL CAPACITY OF AIR NODES
C
      KM1=K-1
      DO 220 I=1,KM1
      YY(I)=RHOAIR*CPAIR*DELX
  220 CONTINUE
      YY(K)=(RHOAIR*CPAIR*DELX)+(TRMASS*CPSTL)
C
C
      WRITE (6,39) DESCR
C
C
C
      WRITE(6,40)
      WRITE(6,42)
      WRITE(6,41)
      WRITE(6,43)
      WRITE(6,44)
      WRITE(6,45)
      WRITE(6,80) CPAIR,RHOAIR,KAIR,KMIX,TI,THETA
      WRITE(6,48)
      WRITE(6,49)
      WRITE(6,81) K,N,M,MRET,NLTS
      WRITE(6,50)
      WRITE(6,51)
      WRITE(6,52)
      WRITE(6,82) PER,AREA,UWALL,DELX
      WRITE(6,30)
      WRITE(6,31)
      WRITE(6,32) TRMASS,CPSTL,SF
      WRITE(6,53)
      WRITE(6,54)
      WRITE(6,55)
      DO 225 I=1,NROOF
      WRITE(6,83) (RNAME(J,I),J=1,5),THRF(I),KRF(I),RHORF(I),
     +CPRF(I)
  225 CONTINUE
      WRITE (6,53)
      WRITE(6,18)
      WRITE (6,55)
      DO 230 I=1,NFLOOR
      WRITE (6,83)(FLNAME(J,I),J=1,5),THFL(I),KFL(I),RHOFL(I),CPFL(I)
  230 CONTINUE
C
```

```
C REENTRY POINT AFTER EACH COMPLETE DAY
C
      DO 1080 NDAYS=1,ND
C
      WRITE (6,40)
      WRITE (6,88) NDAYS
      WRITE (6,41)
C
C
C REENTRY POINT AFTER EACH HOUR
C
      DO 1050 NHOURS=1,NHO
C
      WRITE (6,41)
      WRITE (6,89) NHOURS
      WRITE (6,41)
C
C
C SET ALL HOURLY LOAD SUMMATIONS TO ZERO
C
      SOLLD=0.0
      RFCLD=0.0
      FLCLD=0.0
      WALCLD=0.0
      RFRLD=0.0
      VENTLD=0.0
      RETLD=0.0
      RFST=0.0
      EXLD=0.0
C
C INITIALIZE TEMPERATURES AND FLOWRATES FOR THIS HOUR
C
      SAT=HSAT(NHOURS)
      TS=HTS(NHOURS)
      TO=HTO(NHOURS)
C
C CALCULATE CONVECTIVE AND RADIANT PORTIONS OF LIGHTING LOAD
C
      DO 240 I=1,K
      LTCLD(I)=0.0
  240 CONTINUE
      LTRLD=HLTS(NHOURS)*PERRLT
      LTCLD(NLTS)=HLTS(NHOURS)*(1-PERRLT)
C
C INITIALIZE ELEMENT HEAT LOADS FOR THIS HOUR
C
      DO 250 I=1,K
      LOAD(I)=HLOAD(I,NHOURS)
  250 CONTINUE
C
C THE NEXT TWO DO-LOOPS EVENLY DISTRIBUTE THE CONDITIONED SPACE LOADS
C
      ATL=0.0
      DO 260 I=1,N
      ATL=LOAD(I)+ATL
  260 CONTINUE
      DO 270 I=1,N
```

```
      LOAD(I)=ATL/N
  270 CONTINUE
C
C
C THE NEXT TWO DO-LOOPS EVENLY DISTRIBUTE THE CONVECTIVE LIGHTING
C LOAD INTO THE CONDITIONED SPACE
C
      CMG=LTCLD(NLTS)
      DO 290 I=1,N
      LTCLD(I)=CMG/N
  290 CONTINUE
C
C
C
C INITIALIZE SUPPLY,RETURN AND VENTILATION IN ELEMENTS
C
      HVENT(NHOURS)=HSUP(NHOURS)-HRET(NHOURS)
      DO 300 I=1,N
      MSE(I)=HSUP(NHOURS)*60.*RHOAIR/N
  300 CONTINUE
      MRE(MRET)=HRET(NHOURS)*60.*RHOAIR
      MVE(M)=HVENT(NHOURS)*60.*RHOAIR
      MS=HSUP(NHOURS)*60.*RHOAIR
      MR=HRET(NHOURS)*60.*RHOAIR
      MV=MS-MR
C
C CALCULATE CIRCULATION BETWEEN ELEMENTS
C
      MCE(1)=MSE(1)-MRE(1)-MVE(1)
      KM1=K-1
      DO 305 I=2,KM1
      MCE(I)=MSE(I)+MCE(I-1)-MRE(I)-MVE(I)
  305 CONTINUE
C
C REENTRY POINT AFTER EACH TIME STEP
C
      DO 1010 NSTEPS=1,NSTP
C
C
C
      HRO=3.0
      DTFL=ABS(T(NFL)-T(NAIR))
      HFI=1.7*(DTFL)**.25
      HRI=.35+(.30*((MVE(M)/7.0)**.8))
C
C
C
C CALCULATE COMMON COEFFICIENTS (FOR AIR NODES)
C
      C1=THETA/(RHOAIR*CPAIR*DELX)
      C6=THETA/((RHOAIR*CPAIR*DELX)+(TRMASS*CPSTL))
      C2=THETA/(RHOAIR*DELX)
      C7=THETA*CPAIR/((RHOAIR*CPAIR*DELX)+(TRMASS*CPSTL))
      C3=(THETA*(KAIR+KMIX))/(RHOAIR*DELX*DELX*CPAIR)
      C8=(THETA*(KAIR+KMIX))/((((RHOAIR*DELX*CPAIR)+(TRMASS*CPSTL))*DELX)
      C4=(THETA*UWALL*PER)/(RHOAIR*CPAIR)
      C9=(THETA*DELX*UWALL*PER)/((RHOAIR*DELX*CPAIR)+(TRMASS*CPSTL))
```

```
      C5=(THETA*HFI)/(RHOAIR*DELX*CPAIR)
      C10=(THETA*HRI)/((RHOAIR*DELX*CPAIR)+(TRMASS*CPSTL))
C
C INITIALIZATION OF A ARRAY
C
      DO 310 I=1,II
      DO 310 J=1,II1
      A(I,J)=0.0
  310 CONTINUE
      DO 312 I=1,II
      A(I,I)=1.0
  312 CONTINUE
C
C CALCULATE RADIATION COEFFICIENT(FLOOR TO ROOF)
C
      RC=(SIGMA*SF*((T(KAI+1)+460)**4.-(T(NFL)+460)**4.))
     +/(((1/EPS1)+(1/EPS2)-1)*(T(KAI+1)-T(NFL)))
C
C CALCULATE COEFFICIENTS FOR ROOF NODES
C
      DO 315 I=1,NROOF
      DELXX(I)=THRF(I)/2.0
  315 CONTINUE
      D1=(2*THETA*KRF(1))/(RHORF(1)*DELXX(1)*DELXX(1)*CPRF(1))
      D2=(2*THETA*HRO)/(RHORF(1)*DELXX(1)*CPRF(1))
      A(II,II-1)=-D1/(1+D1+D2)
      A(II,II1)=(T(II)+D2*SAT)/(1+D1+D2)
      D1=(2*THETA*KRF(NROOF))/(RHORF(NROOF)*DELXX(NROOF)*DELXX(NROOF)
     +*CPRF(NROOF))
      D2=(2*THETA*HRI)/(RHORF(NROOF)*DELXX(NROOF)*CPRF(NROOF))
      D3=(2*THETA*RC)/(RHORF(NROOF)*DELXX(NROOF)*CPRF(NROOF))
      A(KAI+1,NFL)=-D3/(1+D1+D2+D3)
      A(KAI+1,KAI)=(-D2)/(1+D1+D2+D3)
      A(KAI+1,KAI+2)=(-D1)/(1+D1+D2+D3)
C ***************************************
C
C COMMENT OUT THIS LINE WHEN COMPARING THIS MODEL TO THE STEADY STATE
C MODEL-- OTHERWISE LEAVE THIS LINE IN
C
      A(KAI+1,II1)=T(KAI+1)/(1+D1+D2+D3)
C
C ***************************************
C THESE TWO LINES ARE TO BE USED ONLY FOR COMPARISON TO THE STEADY
C STATE MODEL--COMMENT THEM OUT WHEN MAKING ACTUAL RUNS
C
C     D4=2*THETA/(RHORF(NROOF)*CPRF(NROOF)*DELXX(NROOF))
C     A(KAI+1,II1)=(T(KAI+1)+QROOF*D4)/(1+D1+D2+D3)
C
C ***************************************
      NM1=NN-1
      DO 318 I=2,NM1,2
      KK=I/2
      D1=(THETA*KRF(KK))/(RHORF(KK)*DELXX(KK)*DELXX(KK)*CPRF(KK))
      A(II1-I,II-I)=-D1/(1+2*D1)
      A(II1-I,II1-I+1)=-D1/(1+2*D1)
      A(II1-I,II1)=T(II1-I)/(1+2*D1)
  318 CONTINUE
```

```
      IF(NROOF.LE.1.0) GO TO 320
      NM3=NN-3
      DO 319 I=2,NM3,2
      KK=I/2
      KK1=KK+1
      D1=(2*THETA)/(RHORF(KK)*DELXX(KK)*CPRF(KK))
      D2=(2*THETA)/(RHORF(KK1)*DELXX(KK1)*CPRF(KK1))
      A(II-I,II1-I)=(-(D1+D2)*KRF(KK)/DELXX(KK))/
     +(1+((D1+D2)*KRF(KK)/DELXX(KK))+((D1+D2)*
     +KRF(KK1)/DELXX(KK1)))
      A(II-I,II-1-I)=(-(D1+D2)*KRF(KK1)/DELXX(KK1))/
     +(1+((D1+D2)*KRF(KK)/DELXX(KK))+((D1+D2)*
     +KRF(KK1)/DELXX(KK1)))
      A(II-I,II1)=T(II-I)/(1+((D1+D2)*KRF(KK)/DELXX(KK))+
     +((D1+D2)*KRF(KK1)/DELXX(KK1)))
  319 CONTINUE
  320 CONTINUE
C
C CALCULATE COEFFICIENTS FOR FLOOR NODES
C
      DO 415 I=1,NFLOOR
      DELXFL(I)=THFL(I)/2.0
  415 CONTINUE
      E1=(2*THETA*KFL(1))/(RHOFL(1)*DELXFL(1)*DELXFL(1)*CPFL(1))
      A(1,2)=-E1/(1+2*E1)
      A(1,II1)=-(-T(1)-E1*TFI)/(1+2*E1)
      E1=(KFL(NFLOOR)*2*THETA)/(RHOFL(NFLOOR)*DELXFL(NFLOOR)*
     +DELXFL(NFLOOR)*CPFL(NFLOOR))
      E2=(2*THETA*HFI)/(RHOFL(NFLOOR)*CPFL(NFLOOR)*DELXFL(NFLOOR))
      E3=(2*THETA*RC)/(RHOFL(NFLOOR)*CPFL(NFLOOR)*DELXFL(NFLOOR))
      E4=(2*THETA)/(RHOFL(NFLOOR)*CPFL(NFLOOR)*DELXFL(NFLOOR))
      A(NFL,KAI+1)=-E3/(1+E1+E2+E3)
      A(NFL,NFL+1)=(-E2)/(1+E1+E2+E3)
      A(NFL,NFL-1)=(-E1)/(1+E1+E2+E3)
C ****************************************
C
C COMMENT OUT THIS LINE WHEN COMPARING THIS MODEL TO THE STEADY STATE
C MODEL--OTHERWISE LEAVE IT IN
C
      A(NFL,II1)=-(-T(NFL)-E4*LTRLD)/(1+E1+E2+E3)
C
C ****************************************
C
C THE NEXT LINE IS USED WHEN COMPARING TO THE STEADY STATE MODEL
C ONLY--WHEN MAKING ACTUAL RUNS COMMENT IT OUT
C
C     A(NFL,II1)=(T(NFL)+E4*LTRLD+QFLOOR*E4)/(1+E1+E2+E3)
C
C ****************************************
      NM1=NFL-1
      DO 418 I=2,NM1,2
      KK=I/2
      E1=(THETA*KFL(KK))/(RHOFL(KK)*DELXFL(KK)*DELXFL(KK)*CPFL(KK))
      A(I,I-1)=-E1/(1+2*E1)
      A(I,I+1)=-E1/(1+2*E1)
      A(I,II1)=T(I)/(1+2*E1)
  418 CONTINUE
```

```
      IF(NFLOOR.LE.1.0) GO TO 420
      NM3=NFL-3
      DO 419 I=2,NM3,2
      KK=I/2
      KK1=KK+1
      E1=(2*THETA)/(RHOFL(KK)*DELXFL(KK)*CPFL(KK))
      E2=(2*THETA)/(RHOFL(KK1)*DELXFL(KK1)*CPFL(KK1))
      A(I+1,I)=(-(E1+E2)*KFL(KK)/DELXFL(KK))/
     +(1+((E1+E2)*KFL(KK)/DELXFL(KK))+((E1+E2)*
     +KFL(KK1)/DELXFL(KK1)))
      A(I+1,I+2)=(-(E1+E2)*KFL(KK1)/DELXFL(KK1))/
     +(1+((E1+E2)*KFL(KK)/DELXFL(KK))+((E1+E2)*
     +KFL(KK1)/DELXFL(KK1)))
      A(I+1,II1)=T(I+1)/(1+((E1+E2)*KFL(KK)/DELXFL(KK))+
     +((E1+E2)*KFL(KK1)/DELXFL(KK1)))
  419 CONTINUE
  420 CONTINUE
C
C CALCULATE COEFFICIENTS FOR AIR NODES
C
C
C CALCULATE FLOOR TO AIR CONVECTION COEFFICIENT TO DISTRIBUTE
C IN THE CONDITIONED SPACE
C
      DO 450 I=1,K
      D5(I)=0.0
  450 CONTINUE
      DO 460 I=1,N
      D5(I)=C5/N
  460 CONTINUE
C
C
      IF(MCE(1).LE.0.0) GO TO 500
      IF(MCE(1).GT.0.0) GO TO 520
  500 A(NAIR,NAIR+1)=(-C3+MCE(1)*C2)/(1+MVE(1)*C2+MRE(1)*C2+C3+C4+D5(1))
      A(NAIR,II1)=-(-T(NAIR)-LOAD(1)*C1-MSE(1)*C2*TS-C4*TO-C1*LTCLD(1))
     +/(1+C3+MVE(1)*C2+MRE(1)*C2+C4+D5(1))
      A(NAIR,NAIR-1)=(-D5(1))/(1+MVE(1)*C2+MRE(1)*C2+C3+C4+D5(1))
      GO TO 550
  520 A(NAIR,NAIR+1)=-C3/(1+C3+MCE(1)*C2+MVE(1)*C2+MRE(1)*C2+C4+D5(1))
      A(NAIR,NAIR-1)=(-D5(1))/(1+C3+MCE(1)*C2+MVE(1)*C2+MRE(1)*C2+C4+
     +D5(1))
      A(NAIR,II1)=-(-T(NAIR)-LOAD(1)*C1-MSE(1)*C2*TS-C4*TO-C1*LTCLD(1))
     +/(1+C3+MCE(1)*C2+MVE(1)*C2+MRE(1)*C2+C4+D5(1))
      GO TO 550
  550 IF(MCE(K-1).LE.0.0) GO TO 560
      IF(MCE(K-1).GT.0.0) GO TO 570
  560 A(KAI,II1)=-(-T(KAI)-LOAD(K)*C6-MSE(K)*C7*TS-C9*TO-C6*LTCLD(K))
     +/(1-MCE(K-1)*C7+MVE(K)*C7+MRE(K)*C7+C10+C8+C9)
      A(KAI,KAI-1)=(-C8)/(1-MCE(K-1)*C7+MVE(K)*C7+MRE(K)*C7+C10+C8+C9)
      A(KAI,KAI+1)=(-C10)/(1-MCE(K-1)*C7+MVE(K)*C7+MRE(K)*C7+C10+C8+C9)
      A(KAI,NFL)=-D5(K)/(1-MCE(K-1)*C7+MVE(K)*C7+MRE(K)*C7+C10+C8+C9)
      A(KAI,NAIR)=+D5(K)/(1-MCE(K-1)*C7+MVE(K)*C7+MRE(K)*C7+C10+C8+C9)
      GO TO 600
  570 A(KAI,KAI-1)=(-MCE(K-1)*C7-C8)/(1+MVE(K)*C7+MRE(K)*C7+C10+C8+C9)
      A(KAI,II1)=-(-T(KAI)-LOAD(K)*C6-MSE(K)*C7*TS-C9*TO-C6*LTCLD(K))/
     +(1+MVE(K)*C7+MRE(K)*C7+C10+C8+C9)
```

```
      A(KAI,KAI+1)=(-C10)/(1+MVE(K)*C7+MRE(K)*C7+C10+C8+C9)
      A(KAI,NFL)=-D5(K)/(1+MVE(K)*C7+MRE(K)*C7+C10+C8+C9)
      A(KAI,NAIR)=+D5(K)/(1+MVE(K)*C7+MRE(K)*C7+C10+C8+C9)
      KM1=K-1
  600 DO 650 I=2,KM1
      IF(MCE(I).GT.0.0.AND.MCE(I-1).GT.0.0) GO TO 610
      IF(MCE(I).LE.0.0.AND.MCE(I-1).LE.0.0) GO TO 620
      IF(MCE(I).GT.0.0.AND.MCE(I-1).LE.0.0) GO TO 630
      IF(MCE(I).LE.0.0.AND.MCE(I-1).GT.0.0) GO TO 640
  610 A(NFL+I,NFL+I+1)=-C3/(1+MRE(I)*C2+MVE(I)*C2+2*C3+C4+MCE(I)*C2)
      A(NFL+I,NFL+I-1)=(-C3-MCE(I-1)*C2)/(1+MRE(I)*C2+MVE(I)*C2+2*C3+C4+
     +MCE(I)*C2)
      A(NFL+I,II1)=-(-T(I)-LOAD(I)*C1-MSE(I)*C2*TS-C4*TO-C1*LTCLD(I))/
     +(1+MRE(I)*C2+MVE(I)*C2+2*C3+C4+MCE(I)*C2)
      A(NFL+I,NFL)=-D5(I)/(1+MRE(I)*C2+MVE(I)*C2+2*C3+C4+MCE(I)*C2)
      A(NFL+I,NAIR)=+D5(I)/(1+MRE(I)*C2+MVE(I)*C2+2*C3+C4+MCE(I)*C2)
      IF (I.GT.2) GO TO 615
      A(NFL+I,NAIR)=(-C3-MCE(I-1)*C2+D5(I))/(1+MRE(I)*C2+MVE(I)*C2+
     +2*C3+C4+MCE(I)*C2)
  615 GO TO 650
  620 A(NFL+I,NFL+I+1)=(-C3+MCE(I)*C2)/(1+MRE(I)*C2+MVE(I)*C2+2*C3+C4-
     +MCE(I-1)*C2)
      A(NFL+I,NFL+I-1)=(-C3)/(1+MRE(I)*C2+MVE(I)*C2+2*C3+C4-MCE(I-1)*C2)
      A(NFL+I,II1)=-(-T(I)-LOAD(I)*C1-MSE(I)*C2*TS-C4*TO-C1*LTCLD(I))/
     +(1+MRE(I)*C2+MVE(I)*C2+2*C3+C4-MCE(I-1)*C2)
      A(NFL+I,NFL)=-D5(I)/(1+MRE(I)*C2+MVE(I)*C2+2*C3+C4-MCE(I-1)*C2)
      A(NFL+I,NAIR)=+D5(I)/(1+MRE(I)*C2+MVE(I)*C2+2*C3+C4-MCE(I-1)*C2)
      IF (I.GT.2) GO TO 625
      A(NFL+I,NAIR)=(-C3+D5(I))/(1+MRE(I)*C2+MVE(I)*C2+2*C3+C4-MCE(I-1)
     +*C2)
  625 GO TO 650
  630 A(NFL+I,NFL+I+1)=(-C3)/(1+MRE(I)*C2+MVE(I)*C2+2*C3+C4-
     +MCE(I-1)*C2+MCE(I)*C2)
      A(NFL+I,NFL+I-1)=-C3/(1+MRE(I)*C2+MVE(I)*C2+2*C3+C4-MCE(I-1)*C2+
     +MCE(I)*C2)
      A(NFL+I,II1)=-(-T(I)-LOAD(I)*C1-MSE(I)*C2*TS-C4*TO-C1*LTCLD(I))/
     +(1+MRE(I)*C2+MVE(I)*C2+2*C3+C4-MCE(I-1)*C2+MCE(I)*C2)
      A(NFL+I,NFL)=-D5(I)/(1+MRE(I)*C2+MVE(I)*C2+2*C3+C4-MCE(I-1)*C2+
     +MCE(I)*C2)
      A(NFL+I,NAIR)=+D5(I)/(1+MRE(I)*C2+MVE(I)*C2+2*C3+C4-MCE(I-1)*C2+
     +MCE(I)*C2)
      IF (I.GT.2) GO TO 635
      A(NFL+I,NAIR)=(-C3+D5(I))/(1+MRE(I)*C2+MVE(I)*C2+2*C3+C4
     +-MCE(I-1)*C2+MCE(I)*C2)
  635 GO TO 650
  640 A(NFL+I,NFL+I+1)=(-C3+MCE(I)*C2)/(1+MRE(I)*C2+MVE(I)*C2+2*C3+C4)
      A(NFL+I,NFL+I-1)=(-C3-MCE(I-1)*C2)/(1+MRE(I)*C2+MVE(I)*C2+2*C3+C4)
      A(NFL+I,II1)=-(-T(I)-LOAD(I)*C1-MSE(I)*C2*TS-C4*TO-C1*LTCLD(I))/
     +(1+MRE(I)*C2+MVE(I)*C2+2*C3+C4)
      A(NFL+I,NFL)=-D5(I)/(1+MRE(I)*C2+MVE(I)*C2+2*C3+C4)
      A(NFL+I,NAIR)=+D5(I)/(1+MRE(I)*C2+MVE(I)*C2+2*C3+C4)
      IF (I.GT.2) GO TO 650
      A(NFL+I,NAIR)=(-C3+D5(I)-MCE(I-1)*C2)/(1+MRE(I)*C2+MVE(I)*C2+
     +2*C3+C4)
  650 CONTINUE
C
C
```

```
C
      CALL GAUSS (II,II1,A)
      DO 800 I=1,II
      T(I)=A(I,II1)
  800 CONTINUE
C
C SUMMATION OF LOADS FOR THIS TIME STEP
C
      SOLLD=SOLLD+(SAT-T(II))*THETA*HRO
      RFCLD=RFCLD+(T(KAI+1)-T(KAI))*THETA*HRI
      RFRLD=RFRLD+(THETA*SIGMA*SF*((T(KAI+1)+460)**4.-(T(NFL)+460)**4.))
     +/((1/EPS1)+(1/EPS2)-1)
      FLCLD=FLCLD+(T(NFL)-T(NAIR))*THETA*HFI
      DO 750 I=NAIR,KAI
      WALCLD=WALCLD+(TO-T(I))*UWALL*PER*DELX*THETA
  750 CONTINUE
      EXLD=EXLD+(MV*CPAIR*T(M)*THETA)
C
C CALCULATION OF VENT AND RETURN LOADS FOR THIS TIME STEP
C
      VENTLD=(MV*CPAIR*(TO-TS)*THETA)+VENTLD
      RETLD=(MR*CPAIR*(T(MRET+NFL)-TS)*THETA)+RETLD
      RFST=SOLLD-RFCLD-RFRLD+RFST
C
C
C TEMPERATURE AVERAGING SEGMENT- TO SIMULATE THE
C BUOYANCY FROM CONCENTRATED LOADS
C
  905 DO 910 I=NAIR,KAM1
      XX=T(I+1)+.1-T(I)
      IF (XX.LT.0.) GO TO 920
  910 CONTINUE
      GO TO 940
  920 DO 930 I=NAIR,KAM1
      IF (T(I).LE.T(I+1)) GO TO 930
      XX=(T(I)*YY(I-NFL)+T(I+1)*YY(I+1-NFL))/(YY(I-NFL)+YY(I+1-NFL))
      T(I)=XX
      T(I+1)=XX
  930 CONTINUE
      GO TO 905
  940 CONTINUE
C
 1010 CONTINUE
      SOLD(NDAYS,NHOURS)=SOLLD
      SRFCLD(NDAYS,NHOURS)=RFCLD
      SRFRLD(NDAYS,NHOURS)=RFRLD
      SRFST(NDAYS,NHOURS)=RFST
      SFLCLD(NDAYS,NHOURS)=FLCLD
      SWALCL(NDAYS,NHOURS)=WALCLD
      SLTLD(NDAYS,NHOURS)=LTCLD(NLTS)+LTRLD
      SRETLD(NDAYS,NHOURS)=RETLD
      SVENLD(NDAYS,NHOURS)=VENTLD
      SEXLD(NDAYS,NHOURS)=EXLD
      WRITE (6,84)
      WRITE (6,85)
      WRITE (6,86)
      WRITE (6,87) SAT,TO,TS,HSUP(NHOURS),HRET(NHOURS),HVENT(NHOURS)
```

```
      WRITE (6,60)
      WRITE (6,61)
      WRITE (6,62)
      DO 1013 I=1,II
      IF (I.LE.NFL.OR.I.GT.KAI) GO TO 1011
      WRITE (6,74) LOAD (I-NFL),T(I)
      GO TO 1012
 1011 WRITE (6,75) T(I)
 1012 CONTINUE
 1013 CONTINUE
 1050 CONTINUE
 1080 CONTINUE
      DO 1095 J=1,ND
      WRITE (6,39) DESCR
      WRITE (6,20) J
      WRITE (6,21)
      WRITE (6,22)
      WRITE (6,23)
      DO 1090 I=1,NHO
      WRITE (6,24) I,SOLD(J,I),SRFCLD(J,I),SRFRLD(J,I),SRFST(J,I),
     +SFLCLD(J,I),SWALCL(J,I),SLTLD(J,I),SEXLD(J,I),SRETLD(J,I),
     +SVENLD(J,I)
 1090 CONTINUE
 1095 CONTINUE
      STOP
      END
      SUBROUTINE GAUSS(N,N1,A)
      REAL A(N,N1)
      DO 200 J=1,N
      DIV=A(J,J)
      S=1.0/DIV
      DO 201 K=J,N1
  201 A(J,K)=A(J,K)*S
      DO 202 I=1,N
      IF(I-J) 203,202,203
  203 AIJ=-A(I,J)
      DO 204 K=J,N1
  204 A(I,K)=A(I,K)+AIJ*A(J,K)
  202 CONTINUE
  200 CONTINUE
      RETURN
      END
```

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VITA

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SIMULATION OF THE TRANSIENT BEHAVIOR OF STRATIFIED AIR CONDITIONING SYSTEMS

by

ALAN THOMAS LEARD

B.S., Kansas State University, 1981

AN ABSTRACT OF A MASTER'S THESIS

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ABSTRACT

Concurrent with the increased interest in air conditioning large industrial buildings and manufacturing facilities runs the desire to reduce the costs, both initial and operating, of these systems. One method of plant cooling load reduction is known as thermal stratification. Thermal stratification, in a single story high ceiling building, operates by supplying conditioned air to only the lower occupied level, known as *the conditioned* zone, while allowing the air above the conditioned zone, known as the stratified zone, to remain relatively unaffected.

The purpose of this investigation is to extend the applicability of previous work to include the transient effects present in full-scale industrial buildings. To this end a computer program has been developed, based on the finite-difference method of approximation, for use in calculation of building (roof, air, and floor) temperature profiles in the presence of transient internal, and boundary conditions. Loads are then determined from energy balances using the computed temperatures.

Full-scale experimental verification of the validity of the computed results was not attempted. Limited verification of the validity of these results has been carried out. Comparisons were made to the actual temperature profiles acquired, under steady-state conditions, from the previous model studies. It has been generally concluded that the transient computer program developed here provides an acceptable prediction of the internal conditions present in a stratified air conditioning system.

Computed results indicate that substantial savings (50% reduction of peak load) can be realized through proper location and timing of supply air introduction and of return and ventilation air extraction. Additional savings are possible by proper management of storage effects (e.g., roof mass) and internal load location.