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A Computer Program for Air Temperature and Cooling Load Determination for Stratified-Cooled Industrial Buildings

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ABSTRACT

A computer program has been developed for use in determining time-dependent loads and temperature profiles in stratified-cooled industrial buildings. Program results are presented to illustrate various program options, and interpretation of results is provided to allow explanation of the heat transfer mechanisms operating in such systems.

INTRODUCTION

A stratified-cooled system is one in which the lower, occupied zone of a space is cooled, while the upper zone is left unconditioned. The heat exchange and flow processes produce a naturally stratified upper zone with a temperature profile that increases progressively with height from the controlled lower-zone temperature to the temperature of the ceiling above. The typical application of this type of system is in high ceilinged industrial plants.

Figure 1 presents a representation of such a space with temperature profile and load sources indicated. Internal loads are lights and floor-level (people, equipment) sources. External loads originate at roof and wall surfaces and enter the space as radiation and convection.

It is believed that proper management of the stratified zone can lead to reduction of load in the cooled zone below. This conclusion is supported by the authors' earlier reported work with steady-state scale models (Gorton and Sassi 1982a) and by numerical results from a computer program written to allow computation of temperature profiles and loads in the model space (Gorton and Sassi 1982b).

In the computer program, the individual heat transfer and flow processes were modeled and then combined to produce a calculational scheme representing the interaction of the various processes. Calculated program results were compared to the experimentally determined model results to assure that the calculational algorithms were appropriate. The comparisons demonstrated that the calculated results corresponded very closely to the measured values for a rather wide range of experimental values. This comparison provided confidence that the program's algorithms were sufficiently accurate for load-calculation purposes.

The next step of development, the subject of this paper, was to extend the program to allow for time-dependent inputs (imposed internal loads, air supply rate, and temperature) and to replace the roof boundary condition of constant-rate heat input with an externally driven input to simulate convective and radiant heating. The program was structured to compute the resulting transient-load patterns occuring in the cooled space.

PROGRAM DESCRIPTION

The existing steady-state program was provided with the ability to accept hourly changes in internal loads, in supply air conditions, and outdoor conditions. Outdoor conditions were represented by a sol-air temperature pattern. The sol-air temperature was used as input to a conventional finite-difference representation of the building envelope, consisting of a

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two-layer roof, walls, and concrete slab floor in communication with a deep ground constant temperature.

Details of the original steady-state program structure were provided in the earlier referenced work (Gorton and Sassi 1982b) and are not repeated here. However, for sake of completeness, a brief description of certain program features is provided.

In figure 2 the basic geometry of the system to be modeled is shown. Roof height is specified by the user, as are the heights of supply, return, and ventilation exhaust inlets and of the lights. The space is divided into a specified number of horizontal layers of equal thickness. Supply air distribution is handled by assigning an equal fraction of the total to each of the layers below the specified level of its introduction. Total supply air quantity is divided into return and exhaust fractions, the fractional flows from each individual layer combining and flowing to the appropriate exit location.

Heat input to the roof is calculated from the hourly sol-air temperature. This energy is divided, by the finite-difference equations for the roof, into portions that are stored in the roof structure and those that leave the interior roof surface by convection to the adjacent air and by radiation to the floor of the space.

The lighting load is treated by separating the total into convective and radiant portions. The convective fraction is added to the air layer in which the lighting is located and the radiant portion is transmitted to the floor.

At the floor, radiation from the lights and from the roof is considered to be absorbed at the floor surface. This energy then either flows by conduction to the constant-temperature ground level, is stored, or is convected to the air in the space.

Floor-level internal loads, plus floor convection, are assumed to be distributed in equal fractions to each of the air layers to which conditioned air is supplied. The assumptions of provision of uniform supply air amounts to each layer and of uniform distribution of loads from sources within the cooled zone constitute an assumption of "perfect" air distribution within the space.

Mass and energy balances written for each air layer, along with equations representing the roof and floor systems, constitute a set of equations describing the thermal and flow conditions in the space. These are solved simultaneously for the temperatures of each layer for each time step. Solutions are run for 24-hour periods until the temperatures during one such period are the same (within specified limits) as for the previous period. This procedure eliminates the influence of an arbitrarily chosen set of initial conditions.

Buoyancy effects are treated by comparing the computed temperatures in each layer to discover possible temperature inversions. If inversions are found, a first-law-based averaging procedure is used repeatedly until each layer has a temperature lower than that of any layer above it.

The load on the conditioned lower zone is computed from the calculated temperatures and specified flow rates of supply, return, and ventilative exhaust air.

A complete description of the program and a program listing can be found in Leard (1983). That reference also includes results from a number of test cases run to confirm that the transient program, when run with time-invariant inputs, produced the same results as the earlier steady-state program. Additionally, results providing some insight into the significance of the various design parameters are presented.

TYPICAL RESULTS

The program can be used to determine loads and temperature profiles in a space described by the system input. For purposes of this paper, it was decided to demonstrate program features by developing a series of cases that illustrate the mechanisms leading to load reduction in stratified-cooled systems.

A structure with a 20-foot (6.1 m) high roof and with supply air introduced at the 10-foot level was chosen for the example. A standard sol-air temperature pattern was chosen. Lights were located at the 12-foot (3.7 m) level. Input lighting load was 8 Btu/hr ft^2

(25.2 w/m^2) and internal loads were 30 Btu/hr ft^2 (94.5 w/m^2). Supply air temperature was set at 55°F (12.8°C) and supply airflow was adjusted hourly to maintain a nominal 75°F (23.9°C) temperature throughout the conditioned zone.

Convection Blocking

In figure 3, a comparison of results from two cases is shown, which demonstrates the fundamental feature that makes stratification effective in load reduction, "blocking" of a part of the potential roof load. The results are for a metal-roofed, uninsulated, air-conditioned structure. The "total volume" case is for a uniform space temperature; case 25 is for a 10 feet (3.05 m) cooled zone with an uncooled, stratified zone above.

In the figure, the hourly sol-air temperature imposed on the room is shown along with the roof temperatures (same as the ceiling) and the air temperatures inside adjacent to the roof. For the total volume system, this air temperature is 75°F (23.9°C), for the stratified system, the upper air temperature is seen to rise during the day to a peak of 127°F (52.8°C). Because of the high-temperature stratified air, convection is effectively "blocked" from entering the stratified-cooled space.

The heat gain to the two spaces is shown in figure 4, where the reduction in peak convective heating is seen to be about 78% due to stratification. Further, this represents heating of the upper-zone air, and this energy is not totally transmitted to the lower zone, where it would become cooling load. Instead, this energy is stored, and some is transferred back to the environment at night when the roof cools, as shown by the negative heat gain value by the graph.

Because of the reduced convective loss from the roof to the air, in figure 3 the roof temperature is higher in the stratified case than in the total volume case. This leads to a higher radiant transfer from the roof to the floor, but in figure 4, the difference between the two cases is only 6% maximum. The total heat gain (convection and radiation) from the roof is reduced about 44%, from 114 Btu/hr ft^2 (359.1 w/m^2) to 64 Btu/hr ft^2 (201.6 w/m^2), at 1:00 p.m. (near the peak) by the stratification effect.

The conditions for the cases just discussed are artificial in that an uninsulated metal building would probably not be air conditioned. They were selected to demonstrate the "blocking" effect of stratification. The results shown in figure 4 indicate that, for the stratified system, convection can largely be ignored and attention can be focused on radiant transfer and its effect on lower zone cooling load. For this reason the next comparison, for more reasonable roof structures, is in terms of radiation only.

Insulation and Thermal Mass

In figure 5, the previously discussed radiant heat transfer from roof to floor for case 25 (uninsulated metal roof) is compared to that of case 4 (metal roof with 2-inch (0.51 m) insulation) and case 5 (4-inch (.102 m) concrete with 2-inch (0.51 m) insulation) to investigate the influences of insulation and of thermal mass. Stratification is assumed in all three cases.

Comparison of case 4 to case 25 shows a reduced heat transfer due to the insulation added to the basic roof. Comparison of case 5 to the others shows a further reduction of peak heat transfer rate and a significant shift and spreading of the curve. The latter effect is due to the storage effect of the greater roof mass. The ability to shift the heat-gain pattern can be an important tool in cooling-load management.

Conversion of Heat gain to Cooling Load

To illustrate the sequence of steps converting heat gain by the roof of a stratified system into cooling load in the lower zone, figure 6 is presented. At any hour, the heat input to the roof from the environment is equal to the sum of the energy stored in the roof structure plus that transferred to the inside by radiation and by convection. The radiation received by the floor is stored, conducted to ground, or given up to the space air by convection, at which time it is counted as space-cooling load.

A brief study of the figure indicates that the peak heat input to the roof of 68 Btu/hr ft^2 (214.2 w/m^2) at 12:00 hours is translated into a space cooling load of about 20 Btu/hr ft^2 (63 w/m^2) peaking in the hours 1600 to 1900. The reduction and shift are due to stratification "blocking" (reduced roof convection) and to the insulation and the storage effects of roof and floor structures. Throughout the 24-hour period, convection is seen to amount to less than

6 Btu/hr ft^2 (18.9 w/m^2). Again, this is due to the stagnant, high-temperature air layer adjacent to the roof.

Even with the heavy, insulated roof, some cooling of the upper strata air is noted during the night hours after the roof has cooled (negative roof storage) sufficiently. A similar result was reported by Dean (1975).

Cooled-Roof Effects

As noted several times earlier, radiation is the main avenue of heat addition from the roof to the cool lower zone. It would appear, then, that cooling the roof to reduce radiation would be beneficial in reducing the cooling load. Roof cooling by management of stratification is possible either by putting the return at the roof or by ventilating from the hot-air zone at the roof. The next two figures investigate the consequences of these actions.

In figure 7, the curve for case 5 represents the cooling load for a system with return air inlets at the floor level. The case 7 curve is the same result for return location at the ceiling level. Both cases are for lights and internal loads on from 0800 to 1700 hours.

The high-return system has a consistently higher load, peaking at 66 Btu/hr ft^2 (207.9 w/m^2) compared to the low-return system, which peaks at 53 Btu/hr ft^2 (169 w/m^2). The higher value occurs because of removal of the stagnant air layer at the ceiling. At 1700 hours the roof temperature of the low-return system is 118°F (47.8°C) and the adjacent air is at 105°F (40.6°C). The high-return system has a lower roof temperature, 111°F, (43.9°C), and a much lower air temperature, 82°F (27.8°C). The greater roof-air temperature difference (29°F (16.1°C) versus 13°F (7.2°C)) results in a greater convective load to the system and a greater total load, even though the cooler roof provides a reduction in radiation into the space.

In figure 8 the curves represent cooling loads that result from differing amounts of ventilative air exhausted at ceiling height. Case 22 has 20% of the total supply exhausted (80% to a low return) and case 21 has 30% exhausted (70% return). The extra ventilation air carries part of the space load to the environment. However, make-up air from the environment must be added to replace the ventilated air. So, although this technique provides reduction in space load it does not reduce coil or system load unless the exhausted air is at a higher temperature than the outdoor air required for make-up.

The lower part of the figure shows temperatures of the exhaust air and the outdoor dry-bulb temperature. The curves indicate that with the higher exhaust rate, case 21, no real saving occurs until 1700 hours, just when the unit is shut down. For the lower ventilating rate, case 22, the exhaust air temperature is higher and savings begin to be of some significance earlier in the day.

The major point is that reduction of space load can be realized by ventilating the upper zone, but that careful consideration of the consequences of added outdoor air load on the system load is necessary. Additionally, this discussion neglects any influence of latent loads.

The discussion also assumes ventilating air is required in the plant and that it therefore must be brought in as supply air. Intentional ventilation of the upper zone with unconditioned outdoor air taken in at roof level is not considered here.

SUMMARY

A description of a computer program capable of computing time-varying cooling loads for a stratified-cooled space has been presented. The program is structured to accept hourly changes in internal loads and environmental conditions, to account for storage effects in the sturcture and in the space air, and to determine the resulting space air temperature profiles and space-cooling loads.

The calculational algorithms are the same as those in the earlier and steady-state program version, which has been shown (Gorton and Sassi 1982b) to produce results that compare closely to results from steady-state experiments.

Results from a number of situations of interest were presented. The conditions for these cases were selected to indicate to the reader the type and variety of input required for program use. These exercises also demonstrate how the program may be used during design to determine

the influences of various options in building structure and system configuration.

Additionally, the results were structured to provide a basis for discussion of the mechanisms that operate to make stratification cooling effective. No new conclusions regarding design of such systems were developted, but it is hoped that the discussions provided will allow a clearer understanding of the potential effect of various design options.

ACKNOWLEDGMENT

This work was supported by the Engineering Experiment Station, Kansas State University. We express our thanks to Dr. William Johnson, EES director, and to Dr. Paul Miller, Mechanical Engineering Department Head, for their continuing support of this project.

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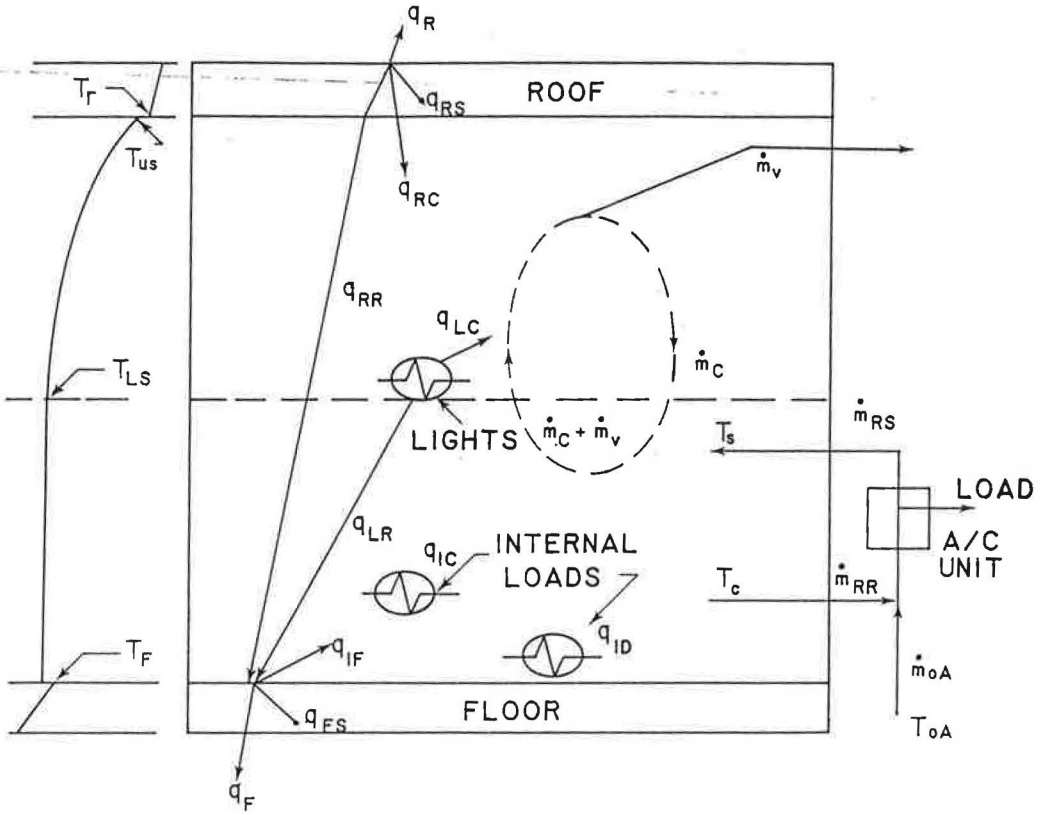

Figure 1. Representation of stratified-cooled system

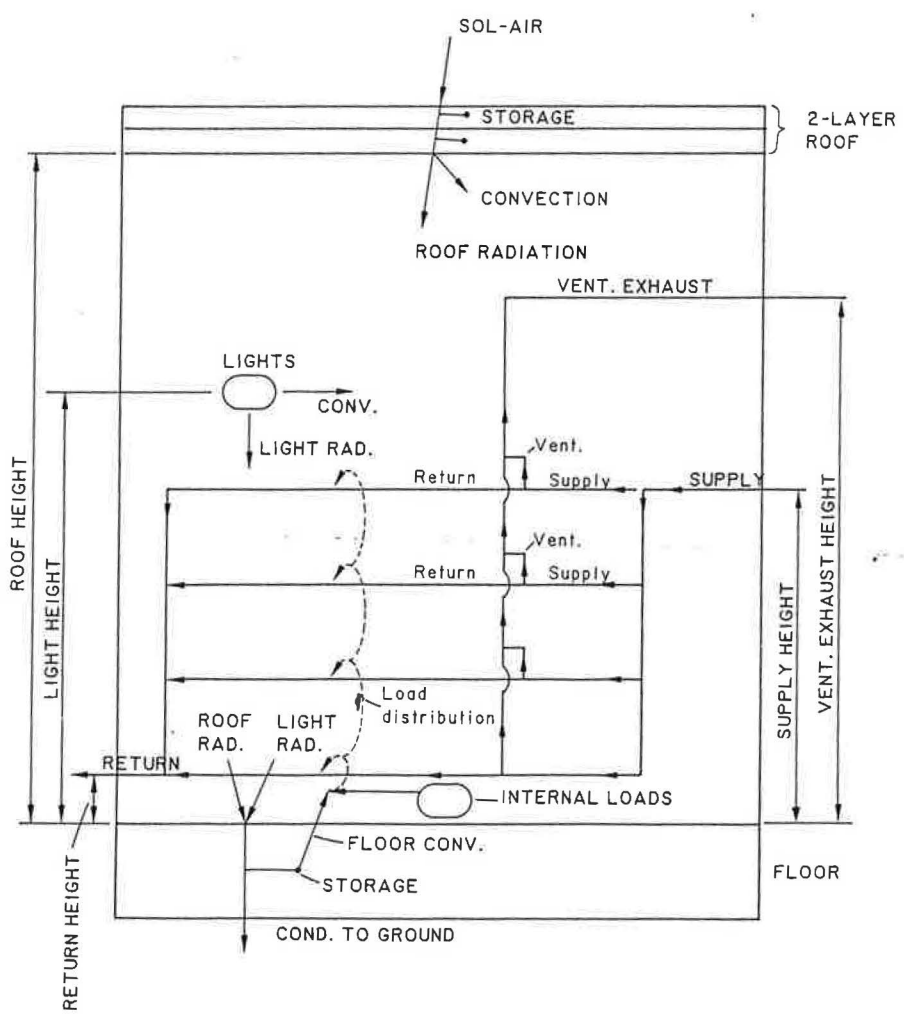

Figure 2. Representation of program model processes

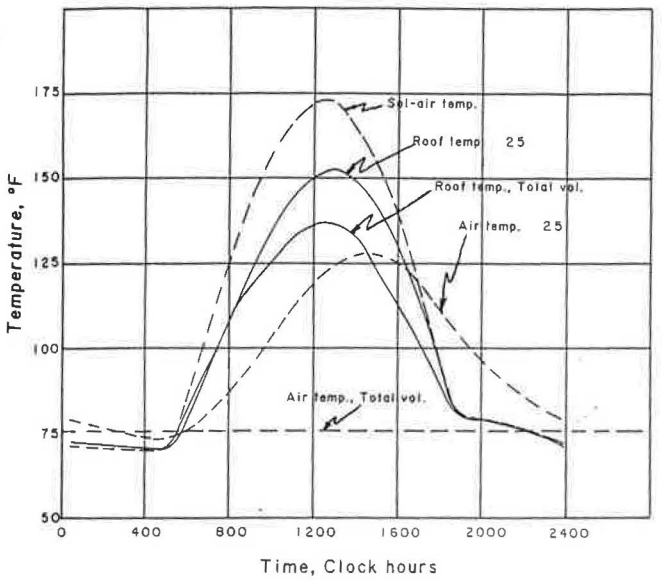

Figure 3. Roof and air temperature: total volume and stratified systems

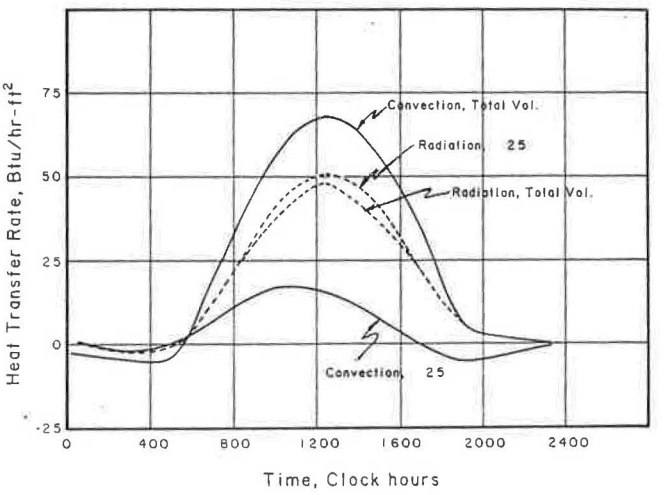

Figure 4. Radiation and convection heat transfer rates total volume and stratified systems

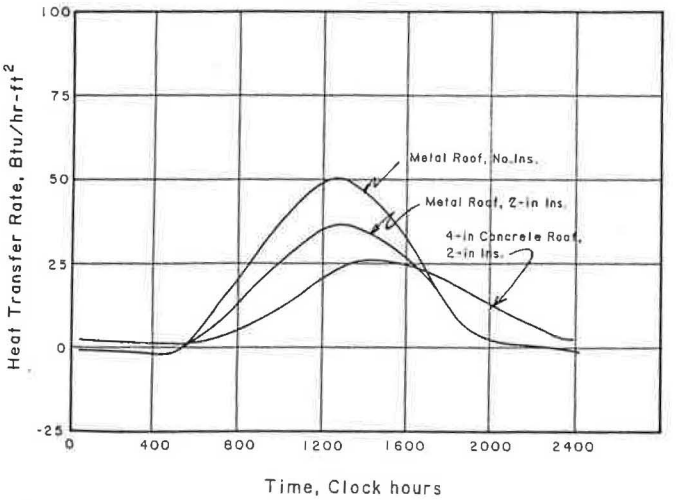

Figure 5. Radiation heat transfer comparison

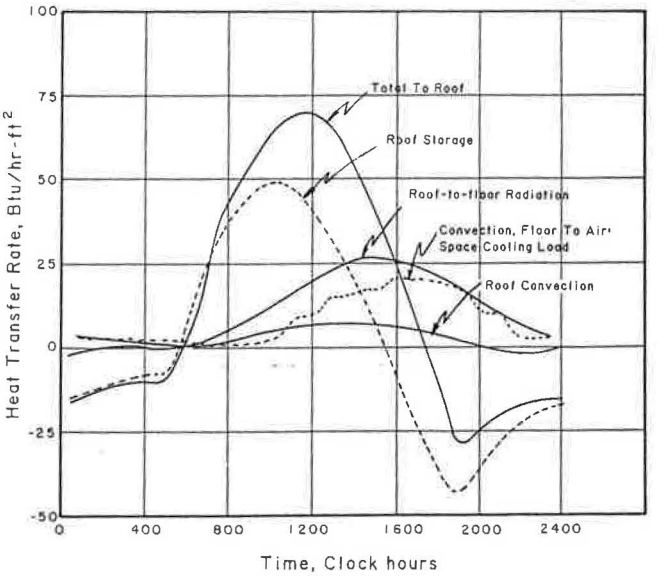

Figure 6. Illustration of convection of roof heat gain to space cooling load

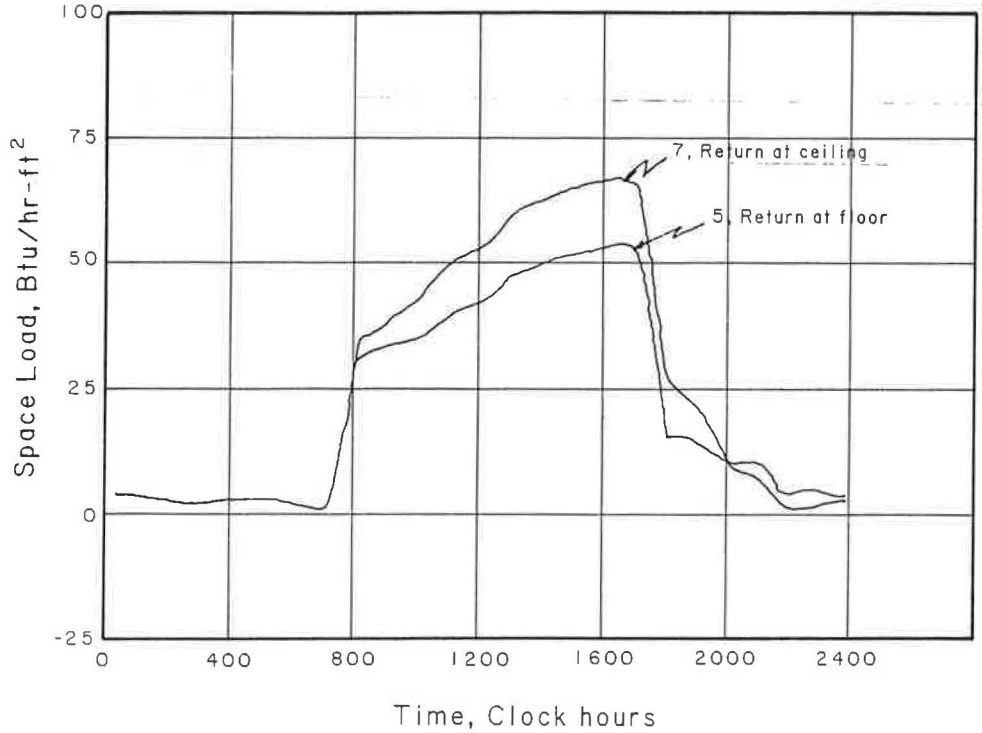

Figure 7. Influence of location of return

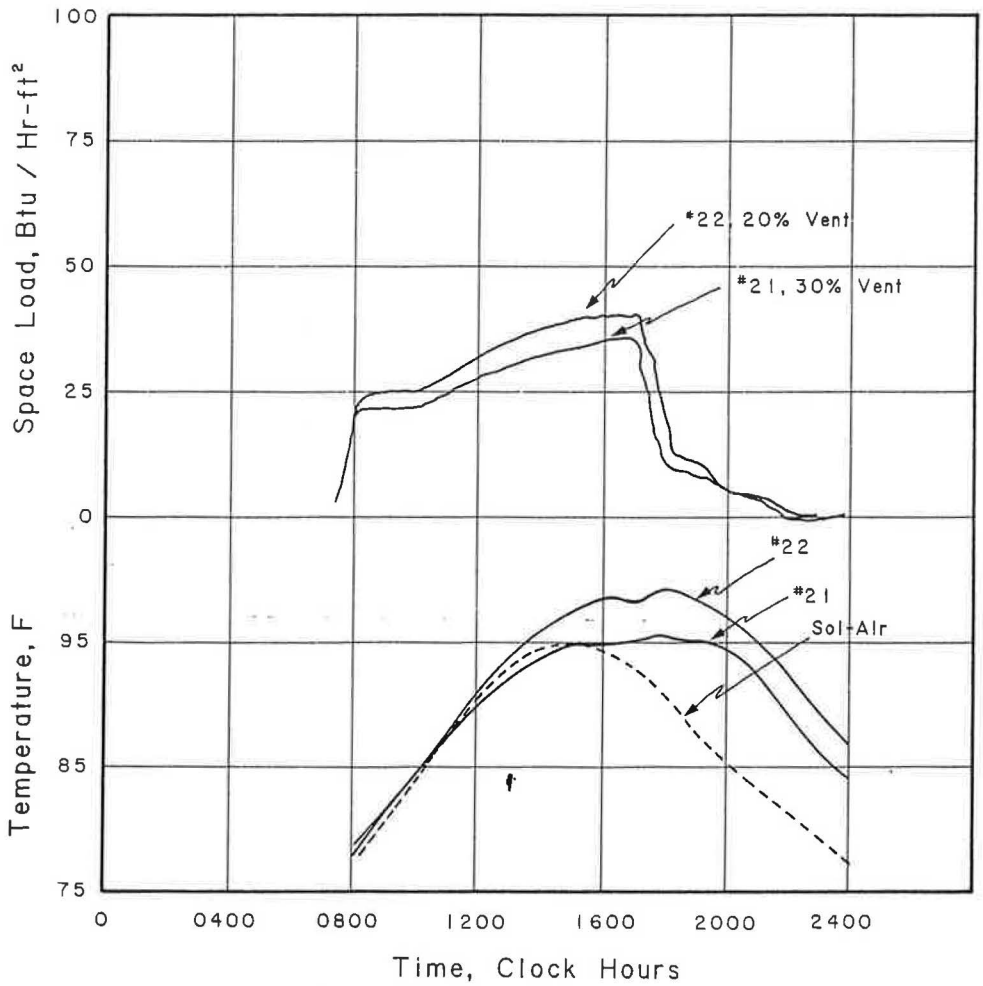

Figure 8. Influence of ventilation rate

DISCUSSION

A. Advani, Safeway Stores, Inc. Oakland, CA: What type of lights were used in your experiment? What percentage of heat was assumed to go up and down?

Gorton: Incandescent bulbs were used. The lights were assumed to emit 80% of their energy as radiation and 20% as convection. In the computer model, the radiant fraction was assumed to be absorbed at the floor and the convection fraction was assigned to the node at the level of the light.

B. Alderman, B. Alderman Assoc., Atlanta, GA: Are there studies or data to predict the results of stratification - how to get uniform temperatures throughout a high interior open space - ie., an atrium?

Gorton: I know of no such data. However, studies of limited scope have been carried out to determine some features of the stratification problem - for example, manufacturer-sponsored studies of the effect of destratifying fans.

Also, it my understanding that ASHRAE is to sponsor research directed at the specific problem of airflow and stratification in atria.