SENSITIVITY ANALYSIS AND EMPIRICAL VALIDATION OF HLITE USING DATA FROM THE NIST INDOOR TEST CELL

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ABSTRACT

Over the past seven years, Ross & Baruzzini, Inc., (R&B) has been working on a project to determine the relationship of the air conditioning load caused by building lighting with time. This effort has been funded by the Electric Power Research Institute.

An initial literature search determined that the basis of existing calculation methods was data generated by Mitalas in the 1970's for a very limited set of experiments. R&B then embarked on an experimental program with the National Institute of Standards and Technology (NIST, formerly National Bureau of Standards, NBS) to more fully investigate variables which might affect the load versus time relationship in present-day buildings. NIST has been funded by the Department of Energy (DoE) for their portion of this effort.

The experimental program included the construction and monitoring of a full scale indoor test cell representative of a typical interior office space. The program also included the creation of a dynamic thermal model to serve as a researcher's tool to allow the numerical simulation of the full-scale test cell. This paper concentrates on the computer model created at NIST, called HLITE (Heat of Lights).

This paper describes the techniques used to empirically evaluate HLITE. Presented from this experimental program are the measured data obtained from the full-scale test cell compared with the results of the HLITE program. The objective is to present the interpretations of these comparisons and to allow other modelers to understand the significance of various parameters within the model.

INTRODUCTION

A computer model, called HLITE (Heat of Lights), was developed at the National Institute of Standards and Technology (NIST), by George Walton (Walton, G. N., 1990). HLITE was developed to extend the results of an experimental program to determine the relationship of the air conditioning load caused by building lighting with time.

In general, HLITE will simulate an office space commonly found in the interior of today's multi-story office buildings, see Figure 1. In particular, this mathematical model was used to simulate the NIST HVAC/Lighting test cell, illustrated in Figure 2. This full scale test cell was constructed and instrumented by NIST and Ross & Baruzzini, Inc., (R&B) to represent a typical interior office space in which to study the interaction between lighting and HVAC systems. The HVAC/Lighting test cell is being monitored for various lighting/cooling loads, surface and air temperatures, and heat flows.

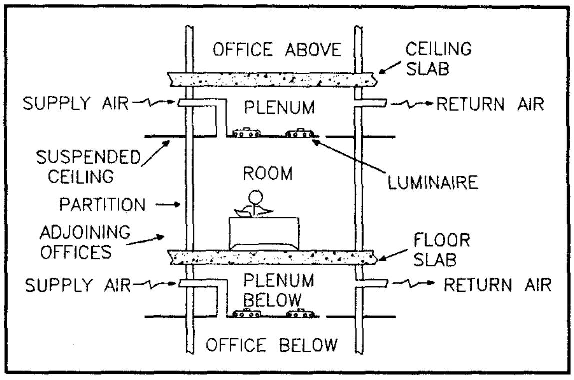

Figure 1 Cross Section of an Interior Office

R&B has compared HLITE simulation results with experimental results generated by NIST in their HVAC/Lighting test cell. The measured data (lighting power input, total cooling loads, and temperatures for plenum air and slab surfaces) have been compared with simulated data, serving to validate the simulation of the thermal processes occurring in the HVAC/lighting test cell.

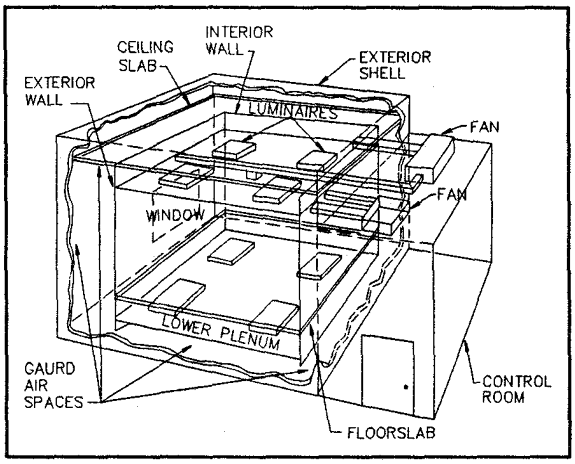

Figure 2 Isometric View of NIST HVAC/Lighting Test Cell

To become a useful tool, HLITE must predict where and how quickly the energy input to the luminaire is distributed, stored, and released within the enclosures (room, plenum, and luminaire) and becomes part of the cooling load. Eventually the model will have adequate flexibility to study the variables that affect the energy transfer from lighting input to cooling load.

These variables are:

- Construction of ceilings, walls and floors.
- Carpeting on the floor slab.
- Various supply and return air configurations.
- Supply air quantity to the room/plenum.
- Ducted return through fixture.
- Spatial dimensions of room and plenum.
- Lighting configuration.
- Furnishings.

This paper describes the techniques used to empirically evaluate HLITE. Presented are the measured data obtained from the full-scale test cell compared with the results of the HLITE program. The objective is to provide interpretations of these comparisons and the sensitivities to variables that affect the energy transfer from lighting input to cooling load.

GENERAL HEAT TRANSFER CONSIDERATIONS

In general, the office space shown in Figure 1 may be divided into three primary enclosures:

1. Room -	the air volume bounded by four walls, the floor slab and the ceiling tile.
2. Plenum -	the air volume bounded by four walls, the ceiling tile and the ceiling slab.
3. Luminaire -	the air volume bounded by the lamp housing and lens, including the ballast and tubes.

Using HLITE, the room, plenum, and luminaire are described in terms of a thermal network which consists of nodes and links. Nodes correspond to some volume of material which can be described by its temperature, and links describe the heat transfer paths between nodes. To simplify the description, those links which share identical thermal characteristics, reference elements which are defined only once.

More specifically, HLITE was used to model the HVAC/Lighting test cell shown in Figure 2. In all, forty-two nodes describe the room, plenum and luminaire enclosures. The room section has individual nodes representing the floor slab upper surface, four 8-ft. (2.44 m) high walls, the suspended ceiling lower surface, and the luminaire lens lower surface. Similarly, the plenum is described by nodes for the ceiling slab lower surface, the metal deck, four 2.5-ft. (.76 m) high walls, the suspended ceiling upper surface, and luminaire housing exterior surface. The luminaire enclosure contains nodes for the lamps, ballast, luminaire housing lower surface, and luminaire lens upper surface.

In all three enclosures, the properties are assumed uniform over each node/surface. Emittances, conductivity, specific heat capacity, temperature, and density are all assumed equally distributed across each enclosure node/surface. Also, radiant, convective, and conductive heat transmissions are assumed uniform.

Because HLITE is a dynamic thermal model, the step response of the HVAC/Lighting test cell to a given step change in lighting input may be simulated. For instance, in the test cell, typically the cooling equipment runs twenty-four hours a day, and the lights are switched on or off for approximately two thirty-six hour cycles. Thus, the transient step response of the lighting and HVAC systems can be studied. The tests are not, however, limited to these typical cycles, as described in two previous reports (Rundquist, R. A. 1990) and (Conniff, J. P. 1991).

HLITE uses a combination of explicit and implicit methods to perform the transient solution of the heat balance equations for each node. The net heat transfer by conduction, convection, infrared radiation and visible radiation is determined for each node. Any net heat gain causes an increase in nodal temperature, representative of heat storage in that particular node.

A primary result of interest is the response of total cooling load (CL), which is a combination of room and plenum cooling loads.

CL = Room Load + Plenum Load

where
room load = heat picked up by the room air
and
plenum load = heat picked up by the plenum air.

Throughout this paper, the response of total cooling load is presented in several families of curves. The cooling load responses shown on these curves have been normalized to the lighting input power because, otherwise, each response curve would approach a different asymptote for lighting input power.

ANALYTICAL VALIDATION

During the development of the program, analytical validation techniques were used to verify the accuracy of the simulation procedures. HLITE was subjected to a basic set of evaluation tests to insure that model is performing as expected. The tests were sequenced so that the most basic algorithms were tested first. These and a thorough theoretical review of the basic physical processes treated by the program have been presented in "A Computer Program for Simulation of HVAC/Lighting Interaction, Interim Report (Walton, G. N., 1990)". Guidance on the use of the program and documentation of the program theory, assumptions, and implementation were also emphasized.

EMPIRICAL VALIDATION

The program documentation and example simulations, supplied by George Walton, were studied to acquire a detailed knowledge of the theoretical basis of the model. This was the first step required for validation work which is ongoing at R&B.

The next step was to double check the thermal characteristics which were used as inputs to model the NIST HVAC/lighting test cell. These were primarily based on handbook values and, where possible, actual measurements were included.

Finally, validation data were obtained for several configurations from the NIST HVAC/Lighting test cell. Effort concentrated on a base case comparison, because it was felt that close agreement with the Base Case would provide a basis for using HLITE to model later configurations. The Base Case configuration of the HVAC/Lighting test cell was 200 CFM supply airflow rate, ceiling grille return, louvered supply air diffuser, four 2-tube acrylic lensed fixtures, without furnishings, with carpet, room-temperature set point = 75°F. The steps used to assure close agreement were as follows:

Step 1: Luminaire energy consumption were matched by adjusting a number of parameters. Actual measurements were used to define the physical characteristics of the luminaire components; i.e., the measured values for the weight of housing, lens, and tubes were all used as inputs to HLITE. As a starting point for the Base Case comparison, the dependence of lighting input power and light output on minimum lamp wall temperature was input into HLITE, based on the typical curves for luminaire performance taken from the 1984 Reference Volume of the IES Handbook.

Step 2: Plenum air temperature was adjusted by adjusting convection coefficients in plenum.

Step 3: Luminaire lamp tube temperatures were compared.

Base Case Comparison

Actual and simulated data for the Base Case comparison are presented in Figure 3 and 4. The curves in Figure 3 represent the response of the HVAC system to a step change in the operation of the lighting system. This response is presented as the cooling load on the HVAC system which has been normalized to the lighting input power and has been plotted against time.

In terms of the test procedure used in the HVAC/Lighting test cell, this is the portion of the test during which the lights were switched on. Prior to and subsequent to this portion of the test, the lights were off for thirty-six hours. The HVAC system ran continuously during the entire test.

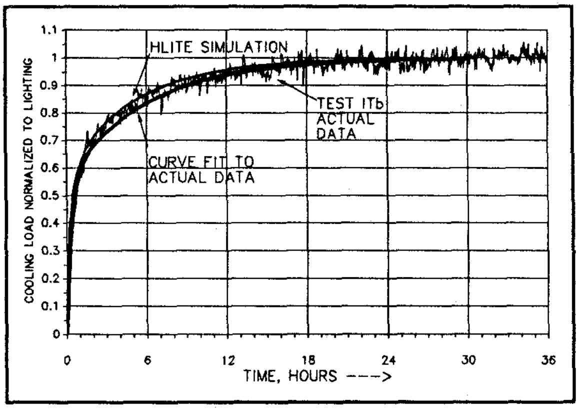

Figure 3 Base Case Comparison with Cooling Load Adapted from Treado, S. J. and J. W. Bean 1990, Figures 11.

The actual data, shown in Figure 3, are bound by two curves; the heavy line represents a NIST regression fit or "curve fit" to the actual data, and the lighter line, which goes through the center of the actual data during the first six hours, represents the HLITE simulation of the Base Case.

It is interesting and encouraging to see the model tracking the actual data more closely than the curve fit during the first six hours. This indicates that the model is handling the short term dynamics better than the regression fit can. The regression fits are the best double exponential representation of the measured cooling load; but the measured cooling load is not a double exponential. Rather, it is a much more complicated function.

The curves in Figure 4 represent the rise in plenum air and floor slab temperatures, which occurred after the lights were switched on, due to the thermal storage of lighting energy. NIST reports that the uncertainty for the actual temperature measurements, presented in Figure 4, is ± 0.75 °F (Treado, S. J. and J. W. Bean, 1990).

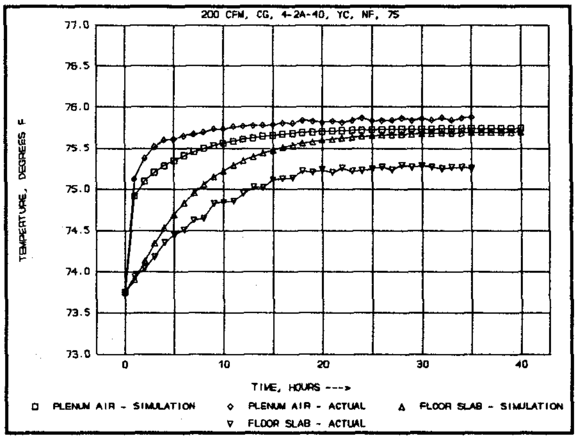

Figure 4 Plenum Air and Floor Slab Comparisons Adapted from Treado, S. J. and J. W. Bean 1990, Figures 8 & 9.

Agreement between the simulated and actual plenum air temperatures is quite good, the values are .125 °F apart, at steady state, which is well within the reported measurement uncertainty. In general, the curves are quite similar in shape, although the faster rise in the actual data, during the first five hours, suggests the plenum air could be picking up the heat off of the plenum surfaces more quickly. The HLITE simulation could be corrected by additional refinement in the convection coefficients used in the plenum.

The temperature agreement for the floor slab is not as good; there is .5 °F temperature difference between the actual and the simulated floor slab. The simulated steady-state temperatures for the plenum air and the floor slab approach asymptotes which are only 0.01 °F apart; this suggests the value selected for the conductivity of concrete is too high. A lower value of conductivity would lessen the heat transfer by conduction up to the room from the plenum below, thus creating a larger temperature gradient throughout the floor slab, i.e., the lower value would force agreement between the simulated and actual floor slab temperature compared in Figure 4. Additional simulations are scheduled to test this sensitivity.

Comparison of Airflow Effects

With the good agreement for the Base Case comparison, additional comparisons can be made. The inputs to HLITE may be varied to simulate different test cell configurations. For instance, the supply air flow rate may be incrementally reduced from the Base Case 200 CFM to 160 CFM, then to 120 CFM, while holding the other inputs constant.

The lower supply air flow rates in the test cell result in a cooling load response which is slower than the response for higher flow rates. This yields a family of response curves, with the 160 CFM bounded by the 200 CFM on the top, and the 120 CFM on the bottom, as shown in Figure 5.

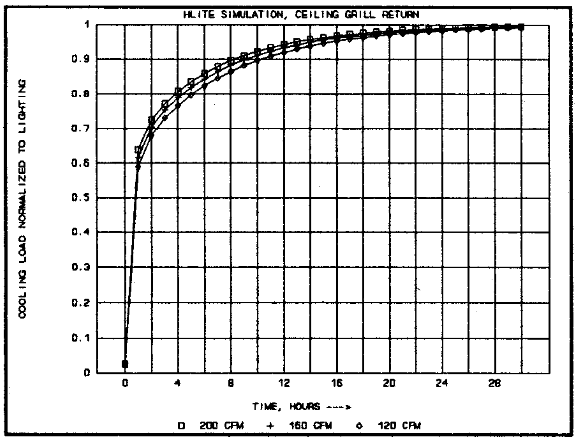

Figure 5 Simulated Response Curves, Three CFMs

In Figure 6, presented as actual data are the cooling response curves for the test cell, which were calculated from recently published fitted coefficients for the Base Case comparison and for two additional supply airflow rates. The simulated response curves for three CFMs, shown in Figure 5 above, are similar shape to the actual response curves shown in Figure 6.

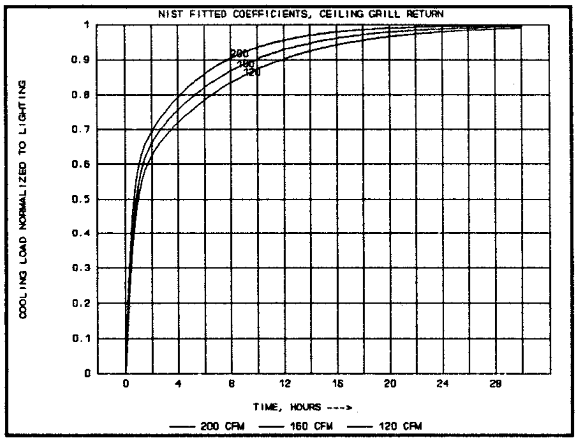

Figure 6 Actual Response Curves, Three CFMs
Adapted from
Treado, S. J. and J. W. Bean 1990, Table 1.

Another input variable which can be varied is the airflow path through the three enclosures: room, luminaire, and plenum. In the test cell, the plenum is used to return the air to the HVAC system; the return air follows one of two paths from the room to the plenum. To aid with the discussion below, these are defined as:

Ceiling Grille Return - The air passes directly from the room, into the plenum via a grille in the suspended ceiling.

Lamp-Compartment Return - The air passes from the room, into the lamp compartment, over the fluorescent tubes, then into the plenum.

The return air path for the Base Case comparison and comparisons discussed thus far, has been ceiling grille return. In Figures 6 and 7, ceiling grille return and lamp-compartment return are compared using the steady state values for the lighting input power and the minimum lamp wall temperature. For each return configuration, these are plotted against three supply airflow rates; ceiling grille return is identified as "CG" and lamp-compartment return is identified as "LC".

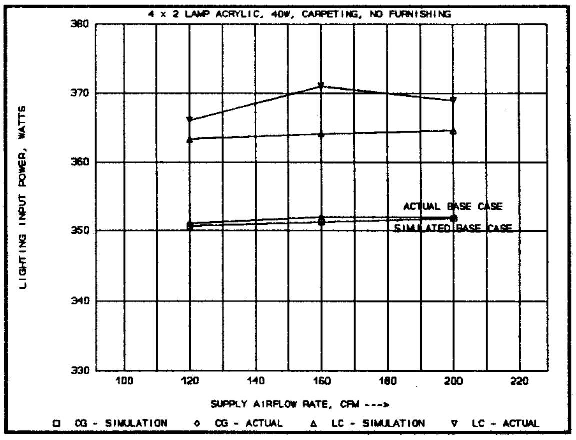

Figure 7 Effects of Airflow on Lighting Input Power

For the Base Case comparison, the simulated lighting input power is well within the ± 4% accuracy for the NIST lighting power measurement (NIST,1990), as can be seen in Figure 7. However, the simulated minimum lamp temperatures, Figure 8, yield poor agreement for the same Base Case. This suggests one of two things: the luminaire performance data, which were input into HLITE, are not applicable for the luminaires installed in the test cell, or the convection and radiation effects, in the luminaire, are not being accounted for correctly. The fact that the opposite is true for the lamp-compartment return reinforces these conclusions.

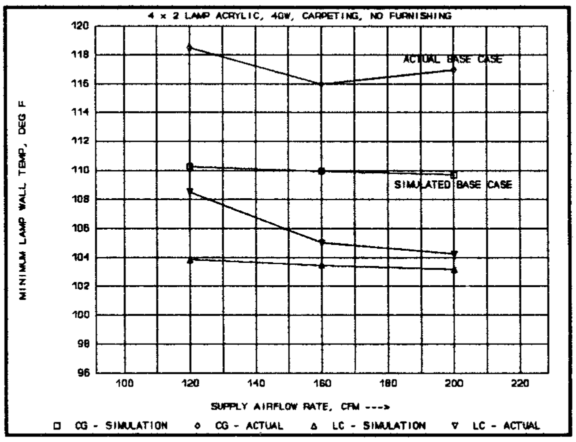

Figure 8 Effect of Airflow on Minimum Lamp Wall Temperature
Adapted from
Treado, S. J. and J. W. Bean 1990, Figure 23.

Comparison of Carpeting Effects

For full-scale testing, carpeting is a relatively simple test cell modification that can dramatically affect the shape of the cooling load response curve. After the lights are switched on, the carpet in the room, warms up more quickly than a bare slab. The carpet stores lighting energy early in the day and immediately releases this energy to the room air, causing higher cooling loads during the first 4 hours, after the lights are switched on. Throughout the day, carpeting acts as an insulator, reducing the upward heat flow from the plenum below, thereby slowing the cooling-load increase later in the day. This results in a cross-over in loads for carpeted and bare slab. This pattern, shown in Figure 9, is consistent with actual test results.

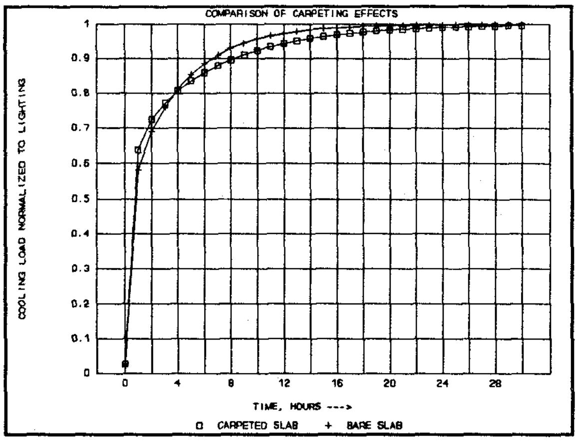

Figure 9 Cooling Load Response, Carpeted vs. Bare Slab

With carpeting, the reduction in heat flow up from the plenum below allows more heat to be stored in the floor slab; thus, the temperatures, shown in Figure 10, are 0.6 °F warmer for carpeted versus bare slab. Specific heat and thermal conductivity are the two properties which were modified in the HLITE input data, to reflect the characteristics of the carpeting.

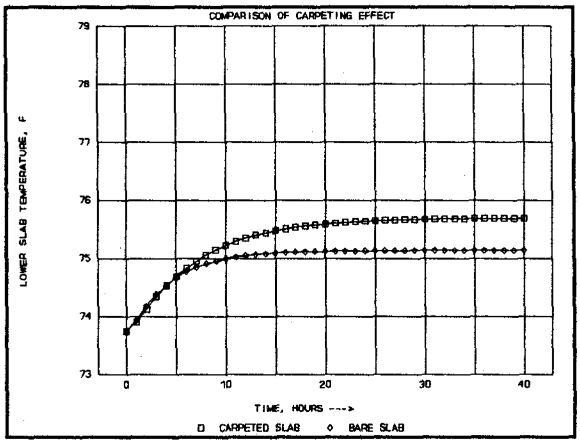

Figure 10 Slab Temperatures, Carpeted vs. Bare Slab

Effects of Slab Thickness

The floor slab is the most difficult parameter to alter in the test cell. To increase the slab thickness, extensive labor is required to remove and reinstall the instrumentation, as the slab thickness is altered. Slab thickness testing have not been run in the test cell; however, it was that felt that preliminary checks of the sensitivities could be shown using HLITE, even though the actual data were not available for comparison. Figures 11 and 12 represent simulated comparisons of various floor slab thicknesses, ranging from 2.5 inches to 18 inches. The is premise that the thicker slab would slow the response of the cooling load.

Figure 11 represents the step response to lighting load for four slab thicknesses. Note, the slab thickness affects the late response.

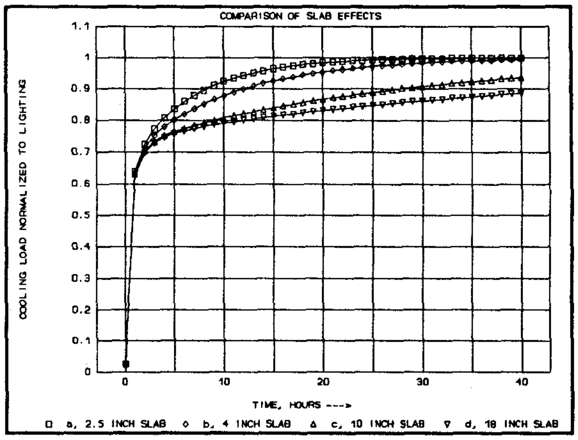

Figure 11 Cooling Load Response, Four Slab Thicknesses

Figure 12 represents the slab temperatures for the same thicknesses.

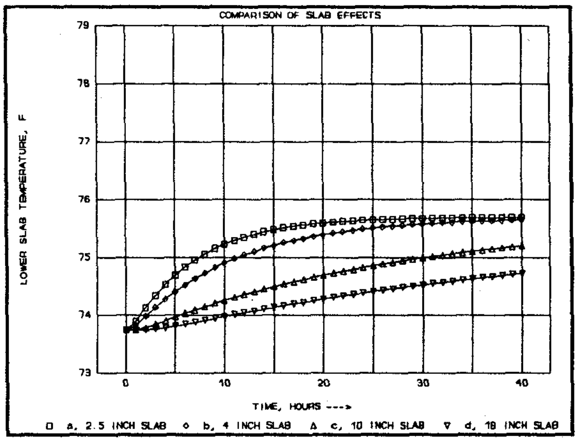

Figure 12 Slab Temperatures, Four Slab Thicknesses

The effects of carpeted versus bare slab are compared in Figure 13 and 14 for a 4-inch and a 18-inch slab thickness. In Figure 13, the cooling load response curves for the 4-inch slab are similar in pattern to those shown for the 2.5-inch slab, in Figure 9. For the 18-inch slab with carpeting, note that response of the cooling load shown in Figure 13 was faster during the first fifteen hours, even though the slab temperatures shown in Figure 14 track each other identically.

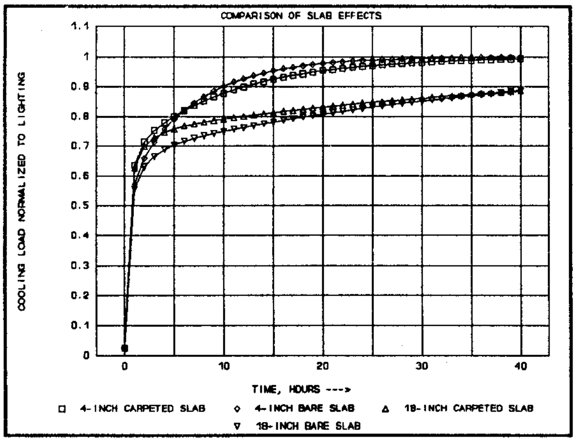

Figure 13 Cooling Load Response, Two Slab Thicknesses Carpeted versus Bare Slab

Presented in Figure 14 are the slab temperature response curves. As was demonstrated in Figure 10, the carpeting is providing an the insulating effect on the lightweight slab, which allows the 4-inch slab to warm up an extra .5 °F. Note this is only true for the lightweight slab as compared to the heavy slab; the carpeting provides less of an insulating effect on the thicker slab.

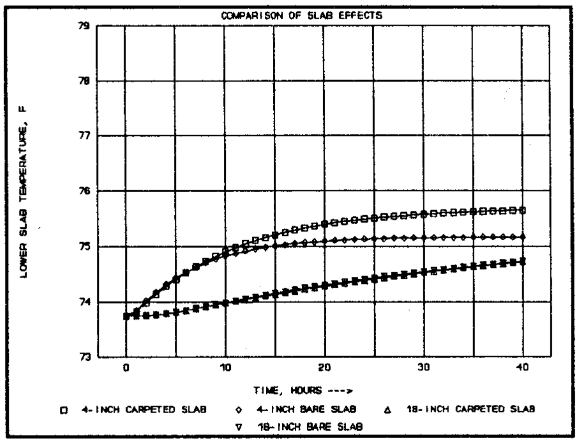

Figure 14 Slab Temperatures, Two Slab Thicknesses Carpeted versus Bare Slab

Comparison of Convection Correlations

To improve the agreement between actual and simulated data for the Base Case comparison, three types of correlations were considered for the convection coefficients in the room and plenum. Two were based on ASHRAE correlations for natural convection (ASHRAE 1989), the other was based on forced convection correlations, derived from an experimental investigation into convective heat transfer in enclosures having high ventilative flow rates (Spitler J. D. 1990).

The primary differences between the three convection coefficient correlations is that one is temperature dependent, another is velocity dependent, and the other is independent of temperature and velocity (the values are held constant during the entire simulation). These are identified, in figures 15 and 16, as "a, ASHRAE Detailed", "c, Spitler", and "b, ASHRAE Simple", respectively.

The correlations recently published by Spitler are especially interesting and useful because these are supported by full-scale testing and address the "ceiling effect". The ceiling effect occurs when a supply air diffuser is used, and the air washes the suspended ceiling tile, thus increasing the convection transfer to and from the ceiling. This is evidenced in the plot showing the convection coefficients in the test room, for each of three convection correlations studied. Note the convection coefficients shown in Figure 15 span a large range. These are presented from left to right, in the order of worst to best agreement for the cooling loads shown in Figure 16.

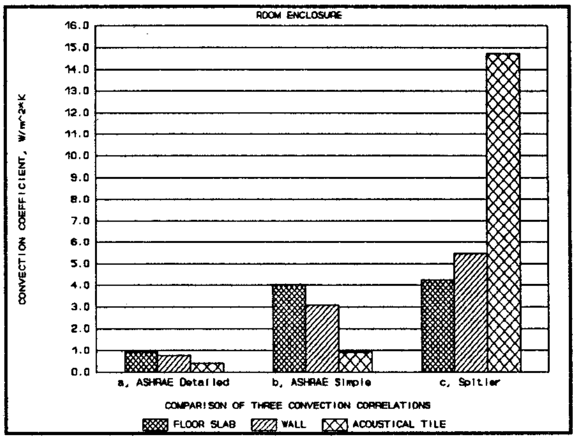

Figure 15 Convection Coefficients for Room Enclosure

Figure 16 shows the cooling load response, normalized to the input lighting power, relative to time. The inverted triangle represents a curve fit to the Base Case comparison. Note the closest agreement is for the Spitler convection correlations.

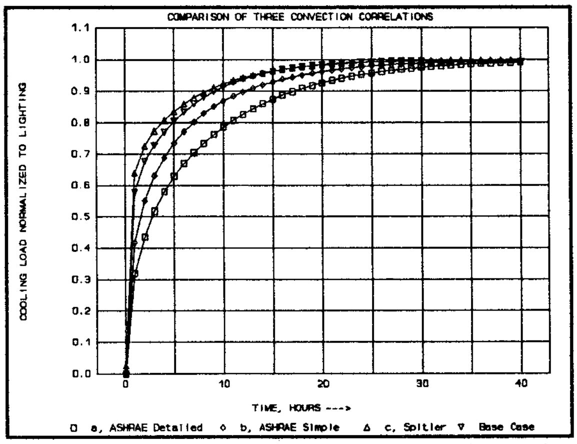

Figure 16 Cooling Load Response, Three Convection Correlations

Although Spitler's correlations worked well for the room enclosure, these correlations were not applicable to the plenum enclosure. The strikingly different airflow patterns in the room and the plenum enclosures is the primary difference which negates the use of Spitler's correlations in a plenum. To retain the velocity dependency of the convection coefficients, the coefficients in Spitler's correlation were altered to more closely reflect what is happening in the test cell. The natural convection component of these modifications were based constants published by ASHRAE for natural convection and the forced component was adjusted to provide close agreement for the plenum temperatures.

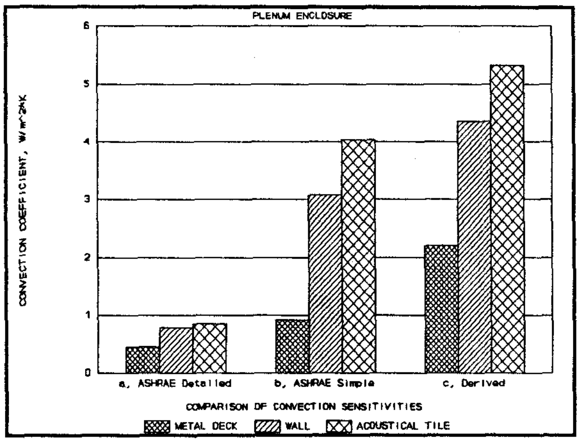

Figure 17 Convection Coefficients for Plenum Enclosure

The fact that the plenum in the test cell is somewhat stagnant is reflected in the lower coefficients which were used in the plenum to achieve good agreement. Figure 16 is a bar chart showing the convection coefficients in the plenum for each of the three convection correlations studied.

FUTURE USES AND PROGRAM DEVELOPMENT SCHEDULE

Computer program development has been delineated into three stages.

The first stage model is a stand-alone detailed lighting interaction design tool, capable of simulating different room, lighting, and HVAC designs. First stage model development has concentrated on the simulation of the NIST lighting test facility, and the formulation and validation of the initial simulation procedures. The stage one model was completed April 1990, with additional effort extending to September 1990 to allow for accurate documentation and additional development.

The second stage model will be distinct from the first stage model, primarily in its ease of use, flexibility and generality. The second stage model will extend the measurement results by simulating configurations not tested due to time and logistical constraints. During the second stage, it is planned to make additional comparisons of the results of HLITE simulations against the extensive test data generated by the NIST lighting test facility. The function to model control actions and necessary HVAC equipment will be added to HLITE. The second stage model is scheduled for completion by September 1991.

Restated below is a description of the third stage model which appeared in NIST's fiscal year 1990 proposal on HLITE.

> "The third stage model is actually a collection of computer algorithms and subroutines for incorporation in whole building energy simulation computer programs. These algorithms are based on the detailed simulation procedures from the second stage model, but are modified to allow incorporation or linkage with other computer programs, such as BLAST, DOE-2, and proprietary programs."

To complete the group of programs necessary to evaluate the HVAC/lighting interaction, NIST intends to add:

- Upgrading the mainframe computer program that evaluates view factors (Walton, G. N., 1990) to the PC environment.
- Developing a computer program to evaluate the distribution of light from a luminaire or using a commercially available program.

CONCLUSIONS

This paper described the methods used to evaluate a computer model called HLITE. HLITE was used to model the NIST HVAC/Lighting test cell, which is representative of an interior office space commonly found in the interior of today's multi-story office buildings. Presented were HLITE simulation results compared with experimental results generated by NIST in their HVAC/Lighting test cell. Measured data for lighting power input, total cooling loads, and temperatures for plenum air and slab surfaces were all compared. The interpretations of these comparisons described the physical process involved and suggested sensitivities which will require additional research.

The computer model is a transient finite-difference formulation using the explicit and implicit solution procedure. To validate the simulation of the thermal processes occurring in the HVAC/lighting test cell, these comparisons will be expanded/repeated to assure correctness as the model is updated during its initial development stages. In the future, HLITE will be used as a tool in a parametric study of room and lighting conditions. With further validation, it will be useful for extending the measurement results to a larger collection of configurations, and for examining additional sensitivities to variables.

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