NISTIR 4472

A COMPUTER PROGRAM FOR SIMULATION OF HVAC/LIGHTING INTERACTIONS: INITIAL REPORT

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Prepared for:
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ABSTRACT

This report describes the initial release of the HLITE program, which simulates the thermal interaction of lighting and HVAC systems. This program was developed to extend the results of an experimental study in HVAC/lighting interaction being conducted at the National Institute of Standards and Technology (NIST). It will serve in planning future experimental test cases and in the development of algorithms that can be incorporated into larger building energy analysis programs. This interim report covers the first phase of the development of HLITE which simulates the NIST HVAC/lighting test facility. Future planned developments will expand its capabilities to larger facilities with more complete thermal interactions. The computer program is based on a simple combined explicit and implicit time integration scheme for a finite volume model which may be applicable to a much broader range of building simulations.

Keywords:

Computer, energy calculation, HVAC, lighting, modeling, transient simulation

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The program described in this report is furnished by the government and is accepted and used by any recipient with the express understanding that the United States Government makes no warranty, expressed or implied, concerning the accuracy, completeness, reliability, usability, or suitability for any particular purpose of the information and data contained in this program or furnished in connection therewith, and the United States shall be under no liability whatsoever to any person by reason of any use made thereof. This program belongs to the government. Therefore, the recipient further agrees not to assert any proprietary rights therein or to represent this program to anyone as other than a government program. Any commercial products or tradenames mentioned in this report are included for informational purposes only, and do not constitute an endorsement or recommendation by the National Institute of Standards and Technology or the Department of Energy.

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1. INTRODUCTION

This report describes the initial release of HLITE, a computer program which simulates the thermal interaction of lighting and HVAC systems. This program was developed to extend the results of an experimental study in HVAC/lighting interaction being conducted at the National Institute of Standards and Technology (NIST) (Treado and Bean, 1988). It will serve in the planning of future experimental test cases and in the development of algorithms that can be incorporated into larger building energy analysis programs. This interim report covers the first phase of the development of HLITE, namely the simulation of thermal processes in the NIST HVAC/lighting test facility.

Therefore, HLITE must accurately model the NIST test facility. HLITE was developed as a research tool rather than an engineering design tool. A primary goal of the program is simulation flexibility; that is, the ability to model a great variety of physical systems and operational strategies including many that were not anticipated during the development of the program. This includes the requirement of a simple fundamental program structure for the addition of new features. Another primary goal is that the simulation be accurate and sensitive to the parameters that the researcher wishes to study. These primary goals dictate that the program be based on fundamental physical principles rather than correlations to the experimental data. Program performance in terms of execution time and program size as well as ease of use are secondary goals.

HVAC/lighting interactions are described in terms of a thermal network. The thermal network is described by a data file which uses keywords and values. Keywords are capitalized in the following description. The primary components of the thermal network are NODEs which correspond to some volume of material which can be characterized by a single temperature, and LINKs which describe the heat transfer paths connecting various NODEs. Since many LINKs have identical thermal characteristics, these characteristics are described once as ELEMENTs, which are referenced by the LINKs. CONTROLs are handled separately; they convert NODE and LINK data such as temperatures and flows to SIGNALs which are processed by other CONTROLs to set values at other NODEs or LINKs.

The HLITE program interacts with data files and other programs as briefly described in figure 1. The user creates a description of the thermal network in a file called the Network Definition File (NDF). This is done with a text editor chosen by the user. Two other files are required to complete the specification of a simulation. The Boundary Values File (BVF) specifies the temperatures of certain nodes in the thermal network and sets the simulation start and stop times. The Discrete Events File (DEF) sets the values of certain signals which provides a flexible scheduling operation. Output is written to various report files defined by the user. Other programs shown in figure 1 will be developed with the next version of HLITE.

HLITE uses a simple finite volume approach to the simulation of transient heat transfer in a room. Nonlinearities in the radiation and convection heat transfer models are handled by linearization and the use of short time steps (on the order of 1 to 5 minutes). These short time steps make it possible to model many of the nodes using an explicit time integration, which is much simpler than an implicit time integration. Since a few nodes may require extremely short time steps for numerical stability, they normally use implicit time integration while the other nodes use the explicit method. Constant time steps are used. Several methods for enhancing the time integration are being tested. Given the scale of the problems to be simulated in this project, these methods should give sufficient performance.

The HLITE program has been developed to run on IBM PC AT compatible computers using the MS-DOS operating system. A math coprocessor is required. Installation of the program is described in the README file on the distribution diskette. It is assumed that the user is familiar with this operating environment. The program is written in the C computer language. This language has excellent facilities for handling simulation problems of different sizes through the used of linked structures and memory allocation.

Section 2 of this report reviews the basics of the numerical methods implemented in HLITE. Section 3 describes how the program is used to perform a simulation. It also summarizes the simulation capabilities of the initial release of HLITE. Section 4 describes some simulations run with the program to test its various features. Section 5 summarizes the features of HLITE and notes possible future developments.

Appendix A gives details of the input files. Appendices B and C give details of the analytic test cases and an experimental test case, respectively.

HLITE is an evolving program. Its capabilities and solution methods will be refined in response to further validation. New capabilities will be added as new needs are identified. The documentation will be revised to reflect those enhancements.

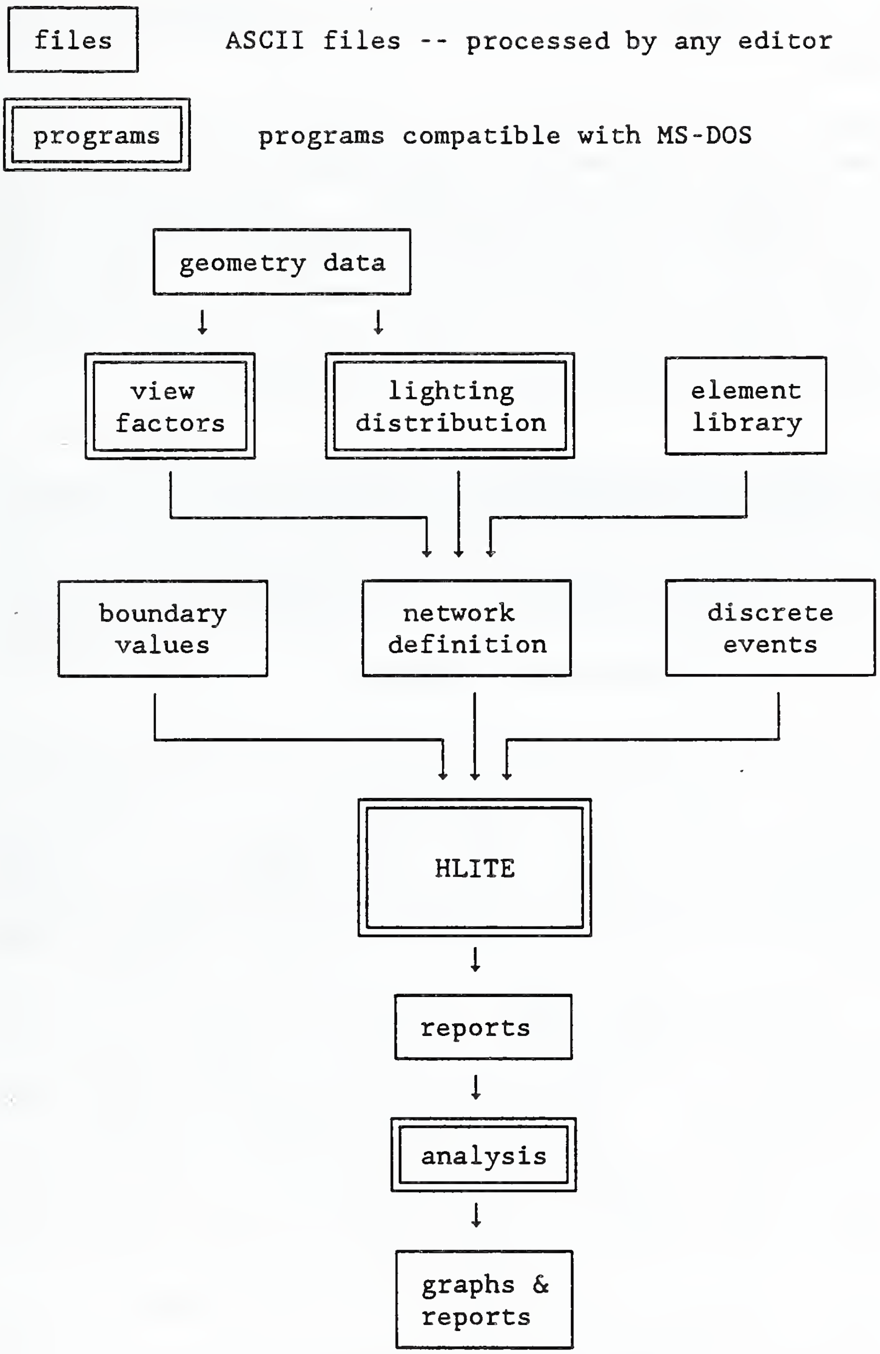

Figure 1. HVAC/Lighting Interaction Computer Model

Notes:

- The view factor and lighting distribution programs are not part of this effort.
- Analysis is done by a commercial program such as LOTUS 1-2-3.

2. NUMERICAL METHODS

2.1 Introductory Example

The development of HLITE centers around the capability to perform transient simulation. A one-dimensional heat conduction problem provides the simplest example to illustrate transient simulation methods. The following figure shows a portion of a one-dimensional conduction problem consisting of two material layers. Temperatures are computed at the boundaries of the layers because of (1) the importance of wall surface temperatures in a room and (2) the possibility of using a more exact finite element method for this analysis. This example will be described by physical instead of mathematical arguments following the description given by Clausing (1969, pp 157-213).

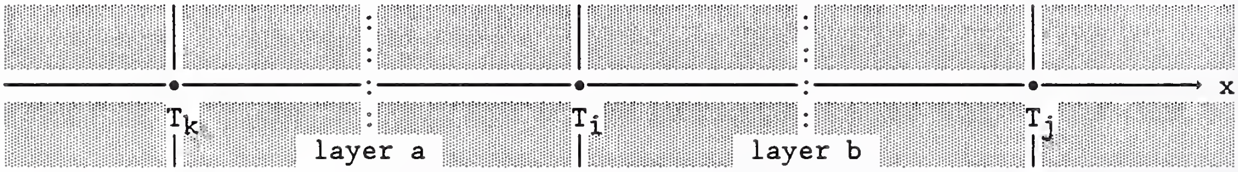

Figure 2. Configuration for one dimensional conduction

The thermal properties of layers a and b are: the thicknesses, L_a and L_b, the thermal conductivities, κ_a and κ_b, the densities, ρ_a and ρ_b, and the specific heats, c_a and c_b. Each layer has identical surface areas, A. Subscripts i and n refer to positions in space and time, respectively. In a lumped parameter representation, the temperature T_i can be considered to represent the temperature of a pseudo-layer extending from the midpoint of layer a to the midpoint of layer b. The internal energy of this pseudo-layer is given by:

$$U_i = \rho\ c\ V\ T_i = \frac{1}{2} (\rho_a c_a L_a + \rho_b c_b L_b) A T_i = C_i T_i \tag{1}$$

which defines the heat capacity, C, assigned to node i. Heat is transferred to and from point i by three paths: conduction from point k:

$$q_a = (T_k - T_i) \kappa_a A / L_a = K_a (T_k - T_i) \tag{2}$$

conduction from point j:

$$q_b = (T_j - T_i) \kappa_b A / L_b = K_b (T_j - T_i) \tag{3}$$

and internal heat generation or radiation absorbed within the layer:

$$q_i = q'' A \tag{4}$$

The change in internal energy of the pseudo-layer between time t_n and t_{n+1} is given by

$$\Delta U_{n \rightarrow n+1} = \Delta t (q_a + q_b + q_i) \tag{5}$$

The calculation of $T_{i,n+1}$ is explicit or implicit depending on when the heat gains are evaluated. Evaluating at time n gives:

$$C_i \ (T_{i,n+1} - T_{i,n}) = \Delta t \ \{ K_a (T_{k,n} - T_{i,n}) + K_b (T_{j,n} - T_{i,n}) + q_{i,n} \} \qquad (6)$$

which is the standard Euler explicit time integration formula. Explicit means that $T_{i,n+1}$ can be directly computed from values known at time n. On the other hand, evaluating at time n+1 gives:

$$C_i (T_{i,n+1} - T_{i,n}) = \Delta t \ \{ K_a (T_{k,n+1} - T_{i,n+1}) + K_b (T_{j,n+1} - T_{i,n+1}) + q_{i,n+1} \} \qquad (7)$$

which is Euler's standard implicit time integration formula. Implicit means that $T_{i,n+1}$ is computed from other values at time n+1. These values depend implicitly on each other and must be computed by a solution of simultaneous equations.

Clausing (1969, p 190) also gives a discussion of stability in terms of thermodynamic laws. Rearranging equation (6) to solve for $T_{i,n+1}$ gives

$$T_{i,n+1} = (K_a T_{k,n} + K_b T_{j,n} + q_{i,n}) \Delta t / C_i + \{ 1 - (K_a + K_b) \Delta t / C_i \} T_{i,n} \qquad (8)$$

There is no solution if $C_i = 0$. If C_i is sufficiently small or Δt sufficiently large, then $(K_a + K_b) \Delta t / C_i > 1$, and as $T_{i,n}$ increases $T_{i,n+1}$ must decrease, and vice versa. This is thermodynamically impossible. It shows up in a numerical solution as oscillations, i.e. "instability", in the node temperatures at each time step. These oscillations tend to quickly increase to totally meaningless values. This suggests a simple technique to determine the minimum stable time step for any element in the system. In general, the smaller the thermal mass of the element, the smaller the time step for a stable explicit solution.

To get an idea of the magnitude of the time scale and size of the mass element for stability consider the case of a homogeneous material with uniform layers. Then $L_a = L_b = \Delta x$, $\kappa_a = \kappa_b = \kappa$, etc., and $\alpha = \kappa/\rho c$. The solution is stable if

$$\Delta x \geq \sqrt{2\alpha\Delta t} \qquad (9)$$

The following values (English units) apply to typical building materials.

material	typical α ft^2/hr	Δt = 3600s	900s	300s	180s	60s
wood	0.0048	Δx = 1.17"	0.59"	0.34"	0.26"	0.15"
glass wool	0.011	1.78	0.89	0.51	0.40	0.23
brick	0.011-0.013	1.86	0.93	0.53	0.41	0.24
glass	0.013	1.93	0.96	0.56	0.43	0.25
concrete	0.019-0.027	2.79	1.39	0.80	0.62	0.36
marble	0.054	3.94	1.97	1.14	0.88	0.51

Rearranging the implicit equation (7) to solve for $T_{i,n+1}$ gives

$$(C_i + \Delta t\ K_a + \Delta t\ K_b)\ T_{i,n+1} = C_i\ T_{i,n} + \Delta t\ (K_a\ T_{k,n+1} + K_b\ T_{j,n+1} + q_{i \cdot n+1}) \qquad (10)$$

This equation shows none of the computational or thermodynamic problems of equation (8) indicating that the standard implicit method is stable for all time steps.

The spatial discretization error for the standard explicit and standard implicit methods is proportional to $(\Delta x)^2$. The time discretization error is proportional to Δt.

The standard explicit and standard implicit methods err in opposite directions. Therefore, a more accurate solution can be obtained by combining the two methods. Expressing this combination generally in terms of β gives:

$$\Delta U_{n \rightarrow n+1} = \Delta t\ \{ (1-\beta)(q_a + q_b + q_i)_n + \beta(q_a + q_b + q_i)_{n+1} \} \qquad (11)$$

where: $0 \leq \beta \leq 1$,

$\beta = 0$ corresponds to the standard explicit method,
$\beta = 1/2$ corresponds to the Crank-Nicholson method,
$\beta = 2/3$ corresponds to the Galerkin method, and
$\beta = 1$ corresponds to the standard implicit method.

Equation (11) can be rearranged to

$$T_{i,n+1} = \{ [C_i + (1-\beta)(K_a + K_b)\ \Delta t]\ T_{i,n} + (1-\beta)(K_a\ T_{k,n} + K_b\ T_{j,n} + q_{i,n})\ \Delta t + \beta(K_a\ T_{k,n+1} + K_b\ T_{j,n+1} + q_{i \cdot n+1})\ \Delta t \} / \{ C_i + \beta(K_a + K_b)\ \Delta t \} \qquad (12)$$

Note that there is no problem for $C_i = 0$. For $\beta \geq 1/2$ this method is unconditionally stable, although the solution may be oscillatory. For $\beta > 3/4$ (approximately) the solution is stable and non-oscillatory. For $\beta = 1/2$, the time discretization error is proportional to $(\Delta t)^2$.

2.2 Explicit or Implicit Time Integration

We may now consider the choice of time integration method. Following the discussion of Belytschko (1983, pp 55, 419, 445), the advantages of explicit time integration are:

(1) Fewer calculations per time step.
(2) Algorithm logic and structure are simple; this implies that it is good for testing new ideas.
(3) Complex nonlinearities are easily handled.
(4) It requires little core storage compared to implicit methods using direct elimination procedures.
(5) It is very reliable in terms of accuracy and completing the computation.

The only notable disadvantage is that explicit time integration is only conditionally stable so that a very large number of time steps may be required.

With regard to accuracy, since implicit methods are unconditionally stable, they can easily be used with too large a time step leading to significant time integration errors. The stability requirements for explicit time integration force the time step to be so small that the time integration error is almost always smaller than the spatial discretization error. Of course, it is also possible to use a spatial discretization that is much too large.

Certain classes of problems require small time steps to achieve suitable accuracy. Long time steps are generally suitable for inertial problems, in which low frequencies dominate the response. Short time steps are required for problems with high frequency transients such as wave propagation problems, for example, simulation of airflow in ducts. Control actions also include high frequency transients.

Press, et.al. (1985) discuss several techniques for the solution of parabolic differential equations. Simple Euler methods are generally considered to be too inaccurate. More advanced methods include Runge-Kutta methods, the Bulirsch-Stoer method, and predictor-corrector methods. They report that the predictor-corrector methods are best for smooth functions. The prediction is explicit while the correction is implicit giving a combination of the characteristics of implicit and explicit methods. The Bulirsch-Stoer method is fully explicit and tends to be more accurate, but is only appropriate for smooth functions. The Runge-Kutta methods are best for non-smooth functions, especially when adaptive step sizes are used. HLITE uses a forward Euler solution, the simplest of all explicit methods, on the grounds that it is probably of sufficient accuracy at small time steps, especially when the uncertainty in knowledge of material properties and convection coefficients is considered. In addition, HLITE is not just solving differential equations; it is creating a finite difference model of a complex reality. It does not seen necessary to solve the finite difference equations to a greater accuracy than they are modeling the physical problem.

Another idea for simulating complex systems comes from work in coupled systems using mixed time integration schemes. The most promising of the mixed time integration schemes that have been described is an implicit-explicit partitioning of the system of equations (Liu & Lin, 1983). That is, the equations for quickly responding elements are integrated using short explicit time steps, and the entire system is integrated implicitly at a long time step. This is in agreement with the prior observation that explicit integration is most applicable to problems with rapidly changing conditions, while implicit integration is best for inertial problems. Some work has been done with combined explicit and implicit modeling for building thermal performance. Sebald (1979) used explicit calculations of the massive elements in passive solar buildings together with implicit calculations for the massless elements. This method was used to reduce the number of simultaneous equations to speed the solution. Relatively long 20-minute time steps were used. Note that this is exactly the opposite of the method used by Liu and Lin, which indicates more study on explicit/implicit methods could be appropriate.

2.3 HLITE Implementation

Two previous computer programs for evaluating the lighting/HVAC interaction (Ball & Green, 1983, and Treado & Bean, 1988) used primarily explicit time integration. This choice is consistent with Belytschko's observations, in that the proposed model needs to deal with control actions (short time steps) and nonlinearities (radiation) while execution time is a secondary concern for a research program. The general philosophy of the HLITE program is to use sufficiently small time steps that nonlinearities can be reasonably approximated in an explicit manner -- the problem is linearized at each time step, and the time steps are assumed short enough that iteration is not needed.

It is likely that the simulation will include a few nodes with very small stability limits, e.g. massless nodes are never stable during explicit time integration. Ball & Green report that one node in their model (plenum air mass) had so little mass that it had to be solved implicitly. HLITE therefore uses a combination of implicit and explicit methods to perform the transient simulation. This allows a variation of the length of the time step and the number of implicit nodes to give maximum program performance. The program determines which nodes should be treated implicitly and which explicitly.

HLITE Computation sequence for one time step:
(1) Set boundary values (from Boundary Values File).
(2) Set control signals (from Discrete Events File).
(3) Process controls to set remaining control signals. (not implemented)
(4) Compute air flows. (not implemented)
(5) Process links to set temperature formula coefficients.
(6) Process nodes to compute explicit temperatures,
simultaneously create list of temperatures to be solved implicitly.
(7) Compute implicit temperatures.
(8) Prepare all nodes for next time step,
simultaneously compute loads at controlled temperature nodes.
(9) Write reports.

All controlled nodes operate at the minimum time step regardless of stability (to process control signals and compute loads).

(1) Boundary value temperatures:

The BVF gives the temperatures of certain nodes as a function of time. Consider a single node which has temperatures $T_{i,n}$ and $T_{i,n+N}$, where difference in time is $N\Delta t$ and the difference in temperature is ΔT. Then

$$T_{i,n+1} = T_{i,n} + \Delta T/N; \quad T_{i,n+2} = T_{i,n+1} + \Delta T/N; \text{ etc.} \tag{13}$$

Algorithm: At time n, $T_{i,n}$ is set and $\Delta T/N$ is stored in the node data structure. At each time step T_i is incremented by $\Delta T/N$ until time n+N. Then $T_{i,n+N}$ is set (to eliminate accumulated round-off errors), the value for $T_{i,n+N+M}$ is read, and the process repeats. Note that the BVF need not use constant time increments, and that the times need not exactly match the time steps. Any mismatch is handled by linear interpolation. (This may be expanded to include flux boundary conditions.)

(2) The DEF gives the values of certain signals. Each line consists of a time, a signal name, and a value. The DEF is checked at each time step and if the current time is greater or equal to the time given on the DEF, the value of the signal is updated.

(3) Process controls: (not yet implemented)

The remaining signal values are processed as indicated by the control links. It is anticipated that the order of evaluation will be important.

(4) Compute air flows: (not implemented)

The airflow network could be solved for the airflows in each link as is done in AIRNET (Walton, 1989). The present method requires that the user specify the air flows.

(5) Calculation of heat fluxes and coefficients:

The heat flux from node j to node i due to conduction, convection, radiation, or air flow is given by

$$q_j = K_j \ (T_i - T_j) \qquad (14)$$

where K_j is the appropriate linear coefficient. Heat gains internal to the node are called q_i. The q values are stored in the appropriate node data structures. The K_j are also stored if the node requires implicit computation.

(6) Calculation of explicit temperatures:

$$T_{i,n+1} = T_{i,n} + dT/dt$$

where

$$dT/dt = \Delta t \ (\sum q_{j,n} + q_{i,n}) \ / \ C_i \qquad (15)$$

The heat gains to node i were computed and summed during link processing. In the multiple time step mode, it is not necessary to recompute dT/dt at every time step.

(7) Calculation of implicit temperatures:

$$T_{i,n+1} = \{ \ C_i \cdot T_{i,n} + [(1-\beta)(\sum q_{j,n} + q_{i,n}) + \beta(\sum K_j \cdot T_{j,n+1} + q_{i,n+1})] \ \Delta t \ \} \ / \ \{ \ C_i + \beta(\ \sum K_j \ ) \ \Delta t \ \} \qquad (16)$$

Note that this step uses heat gains and K_j coefficients which were computed and summed during link processing as for the explicit method, step (5). Therefore, the method is not truly implicit, but relies on the relatively small changes of node temperatures at each time step to give reasonably accurate results. The solution for all temperatures at time n+1 can be expressed in matrix form as

$$[A]\{T\} = \{B\} \qquad (17)$$

where [A] is a square matrix, and {T} and {B} are vectors. The solution of the simultaneous equations is done by a sparse matrix technique which is optimal for a matrix structure in which most of the temperatures are already known from the explicit solutions. The following figure shows the structure of [A] for a case involving 42 equations for 23 explicit nodes and 19 implicit nodes.

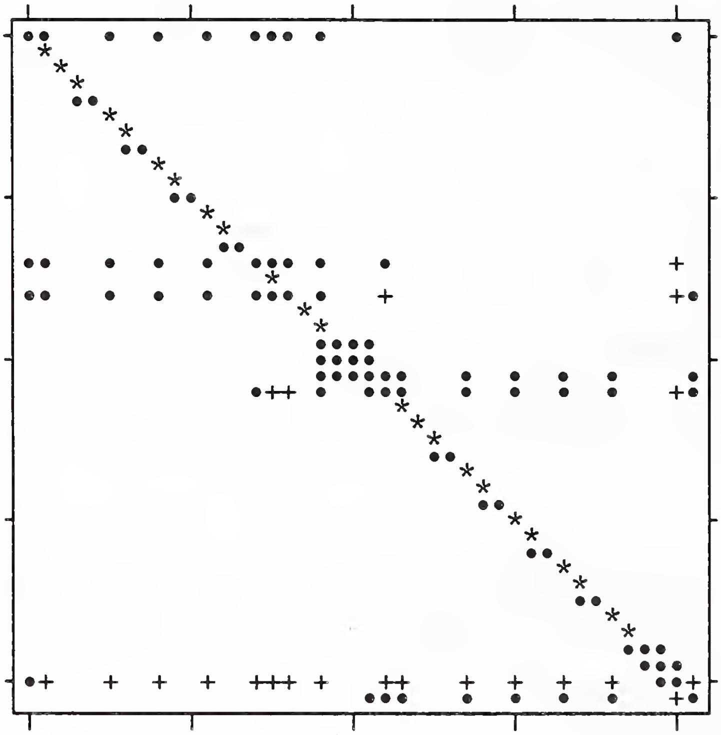

Figure 3. Structure of the [A] matrix

In this figure blanks represent coefficients which must be zero,

- * represents coefficients on the diagonal which must be 1,
- • represents other coefficients which must be non-zero, and
- \+ represents coefficients which are initially zero, but which can become non-zero during solution of the equations.

These equations are diagonally dominant, which implies that pivoting is not necessary in their solution. This allowed the development of a simple sparse matrix solution using a row-wise solution. The sparse solution involves only the • and + elements of [A] for a considerable savings of memory and execution time compared to a full matrix solution. As the time step is shortened, formerly implicit nodes become explicit causing the matrix to become even more sparse and quick to solve.

(8) Heating and cooling loads:

A heating (cooling) load is defined as the rate at which heat must be added to (removed from) a node to cause the temperature to go from $T_{i,n}$ to $T_{i,n+1}$. This heat, Q, is in addition to the naturally occurring heat flows.

$$C_i \; (\; T_{i,n+1} - T_{i,n} \;) = (\; \sum q_j + q_i + Q \;) \; \Delta t \qquad (18)$$

If $T_{i,n+1} = T_{i,n}$, then $Q = -(\sum q_j + q_i)$. Since positive q_j are heat flows into the node, a positive Q is a heatin load and negative Q is a cooling load.

The q_j and q_i may be computed with the explicit or the implicit formula as appropriate for the given node.

Deadband operation requires special processing. Passing from the deadband into a controlled temperature causes the temperature to be reset to the control point and a load computed appropriate to that reset. If the time step begins with the temperature set at a control point and a "negative" load is then computed, the node temperature is revised into the deadband by the amount of that load.

(9) Write reports:

At each time step the variables which are to be integrated, as defined by the user, are processed. If the time step matches the reporting time step, the designated values are written to files or the terminal.

2.4 Possible Extensions

The need to develop a more flexible method for mathematical modeling of physical systems has long been recognized. It is presently the subject of considerable research using new languages and modeling tools. Lewis and Alexander (1990) believe that many of the features of such a system could be achieved using current methods. Their approach is to extend the assumptions of the explicit finite difference approximation to the full range of thermal processes in a building. They have implemented their ideas in a program called HTB2 which models heat transfer through the building structure, control actions, and HVAC equipment.

HLITE and HTB2 were developed independently, but they share the fundamental idea of explicit time integration. Both programs take advantage of the simplification that can occur using explicit methods with only the penalty of short time steps for stability. However, Lewis and Alexander claim that "information on the behavior of the building at high temporal resolution can be obtained without any increase in computation time". This claim will be tested in section 4.3.

3. SIMULATION FEATURES

Execution of HLITE is controlled interactively. The descriptions of the physical system being simulated and computed results are stored in ASCII files.

3.1 Data Files

HVAC/lighting interactions are described in terms of a thermal network. The primary components of the thermal network are NODEs which correspond to some volume element of material which can be characterized by a single temperature, and LINKs which describe the heat transfer paths connecting various NODEs. Since many links have identical thermal characteristics, these characteristics are described once as ELEMENTs, which are referenced by the LINKs. CONTROLs are handled separately; they convert NODE and LINK data such as temperatures and air flows to SIGNALs which are processed by other CONTROLs to set values at other NODEs or LINKs.

The user creates a description of the thermal network in a file called the Network Definition File (NDF) with a text editor. Two other files are required to complete the specification of a simulation. The Boundary Values File (BVF) specifies the temperatures of certain nodes in the thermal network and sets the simulation start and stop times. The Discrete Events File (DEF) sets the values of certain signals which provides a flexible scheduling operation. Output is written to various user defined report files. These files are described in detail in Appendix A.

Simulation models are provided for the following building/lighting/HVAC features:

- transient one-dimensional conduction in multi-layered walls - each layer being homogeneous with constant thermal properties.
- air in a homogeneous zone; movement of air between zones.
- convection between surfaces and air according to simple or very complex and non-linear formulae.
- radiant interchange between diffuse gray surfaces.
- fluorescent luminaires including temperature dependent lighting and power qualities.
- "generic" equipment to simulate miscellaneous heat gains.
- "generic" mass elements and conductive links to represent additional features.
- fixed set point and dead band control of air temperature.

These models are described in Appendix A. Their use is described in more detail in the test cases provided in Appendix B. These simple features can be combined to describe very complex situations.

3.2 Interactive Execution

The user controls the execution of HLITE interactively through the following sequence of events.

(1) Begin execution of HLITE with the appropriate NDF, BVF, and DEF data files plus HLITE.EXE in the default directory. Enter HLITE.

(2) After displaying a brief program description and disclaimer, HLITE asks for the names of the data files. The first question is

```
> I/O in project files? (y/n)
```

Enter y (for "yes") if the three input data files have the same name except for .ndf, .bvf, and .def extensions. This will create an output file using .out as an extension.
Enter n (for "no") it you want to enter the names of the files individually. HLITE will then request each file name.

(3) HLITE then displays "run control data" which the user may modify by entering n in response to the question

```
> Are these values correct? (y/n)
```

The user may then enter data for each of the run control parameters:

```
> Enter input units: 0 = metric, 1 = English
> [min = 0, max = 1, def = 1]
```

This form of question requires entering an appropriate number between the minimum and maximum values. When a default value is indicated, pressing the ENTER key is equivalent to entering the number. All values in the input files must be consistent with the metric or English units listed in Table 1.

```
> Enter output units: 0 = metric, 1 = English
> [min = 0, max = 1, def = 1]
```

The units of values in all output files are determined by this parameter. Note that HLITE uses SI units in its internal calculations.

```
> Enter implicit integration parameter (beta)
> [min = 0.5, max = 1, def = 1]
```

This refers to the value of β in equation 11.

```
> Enter 0 for steady-state, 1 for transient simulation
> [min = 0, max = 1, def = 1]
```

Although HLITE normally does transient simulation, this parameter will cause it to do a steady-state simulation using the initial values of boundary node temperatures and signal settings.

```
> Enter 2 to report temperature limits, 1 to test, otherwise 0
> [min = 0, max = 2, def = 1]
```

It is important to insure that the temperatures achieved have not exceeded the temperatures specified in the NDF for the stability calculations. Once this is known, it may be desirable to eliminate this test (set the parameter to 0) to save execution time.

```
>  Enter 1 for LOTUS delimiters in reports
>  [min = 0, max = 1, def = 0]
```

This feature adds quote marks around the times and commas after each value in the report files for easier transfer to the LOTUS program.

These parameters may be modified in future versions of HLITE.

(4) Before reading the NDF, the user may request that it be echoed to the terminal and the output file as it is processed by a positive response to

```
>  Echo NDF? (y/n)
```

HLITE will display error messages as the NDF is being processed. Echoing is useful to determine the location of those errors. If there are errors in the NDF, HLITE terminates.

(5) The next step in processing is to determine the stability limits for each node and to set up the pointers and matrix for the implicit equations. The user can review the stability limits by a positive response to

```
>  List stability processing? (y/n)
```

The output file will contain stability information for each node. Of particular importance in the checking of the NDF is the list of all links connecting each node to other nodes. This may help to identify missing or misplaced links.

(6) It is sometimes desirable to find the solution to a schedule that is repeated every 24 hours. The following question permits running the same schedule until successive days are identical.

```
>  Transient initialization? (y/n)
```

No reports are written during this transient initialization.

(7) HLITE is now ready to perform its transient simulation. Simulation can be aborted by a negative response to the following question.

```
>  Continue simulation? (y/n)
```

Otherwise, simulation continues as determined by the BVF.

4. PROGRAM TESTING

Testing is an essential part of the development of a computer simulation. Inaccurate results are not always due to program errors as shown in the SERI report on validation of building energy analysis programs (Judkoff, 1983) which identified seven error sources classified into two groups. External sources are those which are not under the control of the developer of the computer code. These errors include:

(1) differences between the actual weather around the building and the weather used in the simulation;
(2) differences between the actual effect of occupant behavior and those effects assumed by the user;
(3) user error, including inappropriate simplifying assumptions, in deriving the input files; and
(4) differences between the actual thermal and physical properties of the building and those input by the user.

Internal error sources are those contained within the coding of the program. They include:

(1) differences between the actual heat/mass transfer mechanisms and the algorithmic representations of those mechanisms;
(2) differences between the actual interactions of heat/mass transfer mechanisms and those interactions between the algorithms; and
(3) coding errors.

Three types of tests have been used to validate building energy analysis programs. These tests involve comparison to other simulation programs, comparison to analytically calculated results, and comparison to experimental data. The following table from the SERI validation report summarizes the advantages and disadvantages of each method.

VALIDATION TECHNIQUES

Technique	Advantages	Disadvantages
Comparative Relative test of different programs	No input uncertainty Any level of complexity Inexpensive Many comparisons possible	No truth standard
Analytical Test of numerical solution	No input uncertainty Exact truth standard given the simplicity of the model Inexpensive	Does not test the model Limited to cases for which analytical solutions can be derived
Empirical Comparison to measured building performance	Approximate truth standard within accuracy of data acquisition Any level of complexity	Measurement involves some input uncertainty High quality, detailed measurements are time consuming & expensive

The analytic validation tests are best for detecting coding errors. The empirical validation tests are necessary to insure that the actual (as opposed to the anticipated) pyhsical processes are modeled correctly.

4.1 Analytic Tests

A series of simple analytical tests have been developed to insure that HLITE is performing as expected. They are described in detail in Appendix B. The tests are sequenced so that the most basic algorithms are tested first. Later tests of other algorithms often rely on the basic algorithms. The input files for these tests are included on the HLITE distribution diskette to provide the user simple cases that can run directly to gain familiarity with the program, and to maintain the set of test cases which must be run when the program is modified to insure that its current capabilities have not been altered.

TEST1A through TEST1D check the explicit and implicit calculation of heat conduction as well as the processing of the BVF and DEF and the calculation of loads for controlled temperature nodes.

TEST2A through TEST2D check the calculation of transient heat conduction including the use of multiple time steps.

TEST3A and TEST3B check the calculation of loads for air nodes for fixed temperature and dead band control.

TEST4A and TEST4B check the simulation of radiant heat transfer between surfaces.

TEST5A through TEST5C check the various convection algorithms.

TEST6A through TEST6D check the equipment algorithms: the modeling of fluorescent luminaires and the impact of time step on the modeling of small mass, high energy components.

TEST7A and TEST7B check the air flow link calculations.

4.2 Experimental Tests

The experimental results used to test the HLITE program are generated by the NIST test facility as described by Treado and Bean (1988). This test facility is constructed on a large concrete slab within the NIST environmental chamber. The facility is divided into two sections, a large insulated shell enclosing the test room area, and a smaller attached control room for housing instrumentation as shown in figure 4. The overall height is 20 ft. 10 1/2 in. The test room floor slab is elevated to accommodate a lower plenum beneath the floor, and all other room surfaces are adjacent to temperature-controlled guard air spaces. Duplicate lighting and HVAC systems are installed in both the test room plenum and the lower plenum. The test room floor and ceiling slabs are 2 1/2 inch thick concrete built on steel decks supported by a structural steel framework. The walls are constructed of 5/8 inch thick gypsum board fastened to steel studs.

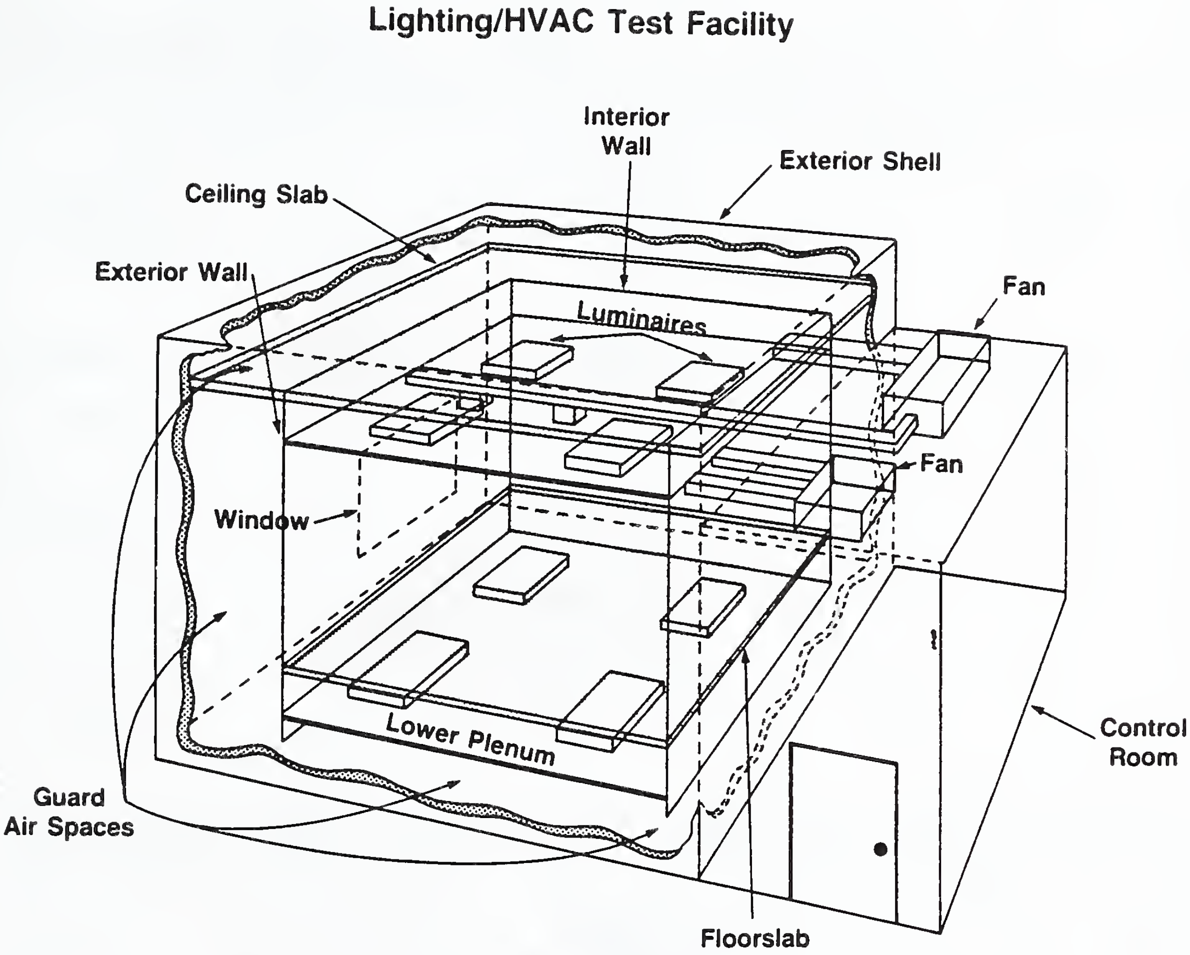

Figure 4. Cut-away Schematic View of Test Facility

The HLITE model is included in Appendix C. Initial results of the modeling are shown in figure 5 which compares the measured and computed transient cooling loads and shows reasonably good agreement between the two. Considerably more data is available than was used in generating this initial comparison. These data, generated over a broad range of operating conditions and lighting configurations, will be used to define a set of modeling parameters which simulate the test room under all those conditions. The results of these comparisons will be reported at a later date.

4.3 Execution Time Tests

Although execution time is a secondary priority in the development of HLITE, some very promising results have been obtained. The impact of various time steps on the explicit/implicit and multistep simulation methods was determined for the 42 node model of the NIST test room. Execution times, in seconds, are for a 25 hour simulation on an IBM PC AT compatible computer.

single time step (s)	number implicit nodes	execution time (s)	multiple time steps (s)	execution time (s)	execution time with reports (s)
1800	42	20.38	1800	20.38	22.09
720	41	46.43	720	46.43	51.92
360	29	48.96	360 720	48.96	-
240	19	43.90	240 720	43.96	49.45
120	5	56.54	120 240 720	54.84	60.66
60	2	93.24	60 120 240 720	73.74	79.51
30	1	171.98	30 60 120 240 720	102.53	108.90

These results show that the execution time increases linearly for time steps of 1800 and 720 seconds when there is a single Euler backward solution for almost all the nodes at each time step. Execution time remains nearly constant for time steps between 720 and 120 seconds. The cost of the increasing number of time steps is compensated by the simplicity of explicit simulation for a greater number of nodes. At shorter times steps (60 and 30 seconds) fewer implicit nodes become explicit so execution times again increase almost linearly. The use of multiple time step is helpful in this range. These results depend on the distribution of critical time steps for the nodes. In this case most nodes have critical time steps between 150 and 400 seconds.

The program uses a direct solution of the implicit equations which has been optimized for the sparsity pattern that occurs when there are only a few implicit nodes among many explicit ones. Reports are a relatively significant execution cost, so they were not generated during these tests because they tend to obscure the computation trends.

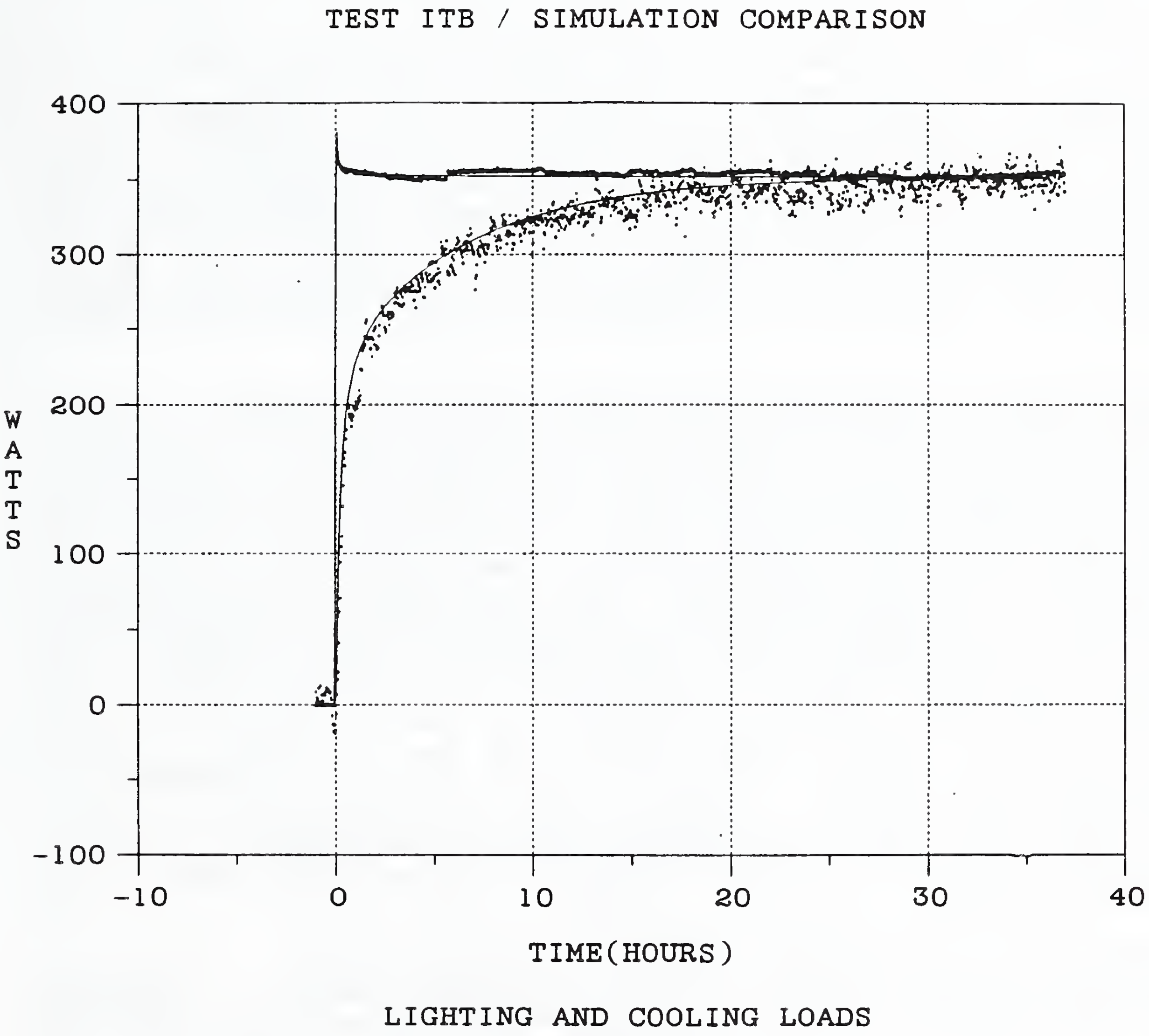

Figure 5. Comparison of Measured and Simulated Cooling Loads

4.4 Planned Tests

In the future, the results of HLITE simulations will be compared against the extensive test data generated by the NIST lighting test facility. These tests may indicate additional features to be added to the program. Certainly, the dynamic control features will be added. Some interesting comparisons to the control actions of the test facility may be possible.

5. CONCLUSIONS

This report has described the initial release of the HLITE program, which simulates the thermal interaction of lighting and HVAC systems. HLITE was developed as a research tool to be used by researchers. Therefore, a primary goal of the program is simulation flexibility, i.e., the ability to model a great variety of physical systems and operational strategies including many that were not anticipated during the development of the program. This includes the requirement of a simple fundamental program structure for the addition of new features. Another primary goal is to provide adequate accuracy and sensitivity to the parameters that the researcher wishes to study.

The choice of the numerical methods used in the HLITE program is based on several factors. The handling of nonlinearities is considered critical. It is believed that control actions will produce the most important and difficult nonlinearities. One method to handle control actions within a long time step model is to note when an action occurs, or should have occurred, and adjust time steps and recompute values accordingly. An alternate method is to use a time step that is so short that the error in the timing of the control action is negligible. A sufficiently short time step combined with a finite volume method can be solved by an explicit time integration scheme. Explicit methods are much simpler and faster for a single time step than implicit methods. The finite volume method provides a simple theoretical basis for defining thermal network components. Explicit methods are especially good at handling nonlinearities. Implicit methods require some form of iteration in solving the simultaneous equations. Iterative methods can encounter difficulties in modeling control actions. The danger of explicit methods is that too long a time step may be used. Some tests have indicated a relationship between the stability limit and the level of accuracy of the model for simple thermal conduction systems.

A forward Euler solution, the simplest of all explicit methods, is probably of sufficient accuracy at small time steps, especially when the uncertainty in knowledge of material properties and convection coefficients is considered. The cyclic nature of building operations tends to cancel the round-off errors over a long time. It is necessary to include the option of implicit integration for some nodes, e.q. massless nodes are unstable at all time steps. This leads to mixed explicit/implicit modeling. Actually, the method is only partially implicit; it uses coefficients computed at the start of the time step, and is therefore subject to error due to nonlinearities. Consider the existence of implicit nodes as a warning signal. This technique does need further testing, but good results have been obtained in the cases examined. The choice of explicit or implicit time integration for each node is based on a simple (approximate) stability test. Different choices for a minimum time step leads to different proportions of implicit and explicit nodes. This makes it possible to trade off the length of the time step with the number of nodes that are solved implicitly or explicitly.

Although program performance in terms of execution time and program size was a secondary goal, very good results were achieved in those areas. The HLITE executable file is about 80,000 bytes long. It can handle a problem of any complexity up to the limits of available memory because storage for all simulation data is handled by memory allocation. In the NIST test room simulation the execution time was approximately constant for time steps from 12 to 2 minutes. This behavior should be very useful in the more detailed modeling of the HVAC system and its controls.

It is planned to compare the results of HLITE simulations against the extensive test data generated by the NIST lighting test facility. The functions to model control actions and necessary HVAC equipment will be added to HLITE. Other plans include upgrading the computer program for evaluating view factors (Walton, 1986) for a PC environment. A computer program to evaluate the distribution of light from a luminaire will be developed. These programs will complete the group of programs necessary to evaluate the lighting / HVAC interaction as originally presented in figure 1.

Although control actions and HVAC equipment have not yet been implemented in HLITE, the experience of the HTB2 program (Lewis and Alexander, 1990) indicates that it may be possible to implement these critical features without a great cost in terms of execution time performance. In fact, the use of simple explicit methods may match very well with the coming generation of multi-processor computers and an apparent trend in using very simple computational methods adaptable to multi-processors (e.g. Monte Carlo ray tracing methods for view factors and lattice gasses for fluid dynamics) instead of traditional methods with very complicated mathematics. The simple explicit methods used in these two programs could provide a general approach to modeling building systems. Such issues should be explored.

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Table 1. Units used in the HLITE program

symbol	description	internal	external metric	external English
t Δt	time or time difference	s	s	s
	simulation time	s	day/hh:mm:ss 000/00:00:00 through 999/23:59:59	
T	temperature	°C	°C	°F
$\underline{T}$	absolute temp.	°K (= °C + 273.15)		-
L	length or thickness	m	m	ft
A	area	m^2	m^2	ft^2
V	volume	m^3	m^3	ft^3
	mass	kg	kg	lb (mass)
ρ	density	kg/m^3	kg/m^3	lb/ft^3
F	air flow rate (referenced to standard air)	kg/s	L/s $\rho = 1.2\ kg/m^3$	ft^3/min (cfm) $\rho = 0.075\ lb/ft^3$
Q	power electric power	W W	W W	Btu/h W
E	energy electric energy	J J	kJ Wh	Btu Wh
κ	thermal conductivity	W/(m•K)	W/(m•K)	Btu/(h•ft•°F)
			[note that the English values are 1/12 of those for Btu•in/(h•ft^2•°F)]	
h	convection coefficient	W/(m^2•K)	W/(m^2•K)	Btu/(h•ft^2•°F)
c	specific heat	J/(kg•K)	kJ/(kg•K)	Btu/(lb•°F)
K	overall conductance	W/K	W/K	Btu/(h•°F)
C	overall heat capacity	J/K	kJ/K	Btu/°F

APPENDIX A: HLITE Data Files

Network Definition File (NDF)

The primary components of the thermal network are NODEs which correspond to some volume of material with a certain temperature, and LINKs which describe the heat transfer paths connecting various NODEs. Since many links have identical thermal characteristics, these characteristics are described once as ELEMENTs, which are referenced by the LINKs. CONTROLs are handled separately; they convert NODE and LINK data such as temperatures and flows to SIGNALs which are processed by other CONTROLs to set values at other NODEs or LINKs.

Almost every item in the NDF is given a name by the user. Names may be up to 19 characters long. They may contain no blanks (use -, _, or selective capitalization instead), and the name "report" is reserved. Names are used instead of numbers to simplify modifying the network and add an element of self-documentation. Choose names to help to document the network. When an input item refers to another named input item, that item must have previously been defined. Because of the possible cross references, it may be safest to define all SIGNALs, all NODEs, all ELEMENTs, all LINKS, and all CONTROLs, in that order. On the other hand, the NDF may be more understandable if physically related items are grouped together. There is some redundancy in the input data which is used to help check for errors.

underline indicates required spelling.
[ ] indicates an optional parameter.
(metric units | English units).
/ in column 1 indicates that the rest of the line is a comment.
* in column 1 indicates the end of the file.

Individual data elements (words) are separated by one or more blanks.

Data past the last required entry on a line is treated as a comment.

Data lines should not be more than 80 characters long.

The first non-comment line in the file must be the TITLE line. The data on this line is echoed as a title in the output report.

SIGNALS:

```
signal  name  type  value
   name   name of signal point.
   type   d = dimensionless,
          t = temperature ( C | F ),
          f = mass flow ( standard L/s | standard ft3/min (cfm)).
   value  initial value.
```

Signal values can be set by data on the Discrete Events File (DEF) or by the operation of control elements. Signal values remain at their initial value until reset by the DEF. Values which are not reset remain at the initial value for the entire simulation.

No control elements have been implemented in this initial version of HLITE.

NODES:

Each node description contains eight identical types of data plus other data specific to the individual type of node. The first word on a node data line is _node_. The second word is a user specified identifier which is unique for each node. The third word is one of the following node types:

air _srf_ _lyr_ _eqp_ _mas_

The fourth word is a single character which tells how the node temperature is determined:

_b_ indicates a temperature from the boundary values file,
_c_ indicates a controlled temperature, and
_v_ indicates a variable temperature.

The fifth word is the fraction of the stability limit, fsl. If the actual time step exceeds fsl times the maximum stable time step, then the implicit solution method is used.

The sixth and seventh words are the expected minimum and maximum node tempearatures. These values are used to determine the maximum stable time step for the node.

The eighth word is the initial temperature of the node.

N.1 air node:

node name air type fsl Tmin Tmax Ti vol [smin smax]

type	temperature type: b, c, or v.
fsl	fraction of stability limit
Tmin	minimum expected temperature (C | F).
Tmax	maximum expected temperature (C | F).
Ti	initial temperature (C | F).
vol	volume (m^3 | ft^3).
smin	if type=c, name of signal for minimum temperature, type t.
smax	if type=c, name of signal for maximum temperature, type t.

The air density and specific heat used to determine the heat capacity of the air node are set at standard default values. Together with the volume, they determine the haet capacity of the air. (A future extension would be to consider humidity and use psychrometric functions to determine air mass and heat capacity.)

The smin and smax signals allow the definition of a deadband with floating temperature between set points, or a set temperature if the set point values are equal. The set point values are guaranteed to be equal if smin and smax refer to the same signal point.

The following values can be reported for air nodes:

T	temperature - instantaneous, averaged.
Q	load - instantaneous, integrated, or averaged (for controlled node).

N.2 surface node:

node name srf type fsl Tmin Tmax Ti area emit [sig]

type	temperature type: b, c, or v.
fsl	fraction of stability limit
Tmin	minimum expected temperature (C | F).
Tmax	maximum expected temperature (C | F).
Ti	initial temperature (C | F).
area	surface area (m^2 | ft^2).
emit	emittance.
sig	if type=c, name of signal setting the temperature, type t.

The heat capacity of a surface node is determined by the material element which is linked to the node.

The surface area is used in determining the conductive and convective heat transfer to adjoining nodes.

The emittance may be used in determining radiant heat transfer to other surface nodes.

The following values can be reported for surface nodes:

T	temperature - instantaneous, averaged.
Q	load - instantaneous, integrated, or averaged (for controlled node).

N.3 layer (actually inter-layer) node:

node name lyr type fsl Tmin Tmax Ti area [sig]

type	temperature type: b, c, or v.
type	temperature type -- a single character: b = temperature from boundary values file, c = controlled temperature, or v = variable temperature.
fsl	fraction of stability limit
Tmin	minimum expected temperature { C | F }.
Tmax	maximum expected temperature { C | F }.
Ti	initial temperature { C | F }.
area	surface area { m^2 | ft^2 }.
sig	if type=c, name of signal setting the temperature, type t.

The following values can be reported for layer nodes:

T	temperature - instantaneous, averaged.
Q	load - instantaneous, integrated, or averaged (for controlled node).

N.4 equipment node:

node name eqp v fsl Tmin Tmax Ti

fsl	fraction of stability limit
Tmin	minimum expected temperature (C | F).
Tmax	maximum expected temperature (C | F).
Ti	initial temperature (C | F).

The surface properties and heat capacity of an equipment node are determined by data in the element and link commands relating to this node.

An equipment node is always subject to a control (defined in the link command) and therefore is simulated at the shortest possible time step in order to catch any changes in the control point status.

The following values can be reported for equipment nodes:
T temperature - instantaneous, averaged.

N.5 mass node:

node name mas type fsl Tmin Tmax Ti area mass c emit sig

type	temperature type: b, c, or v.
fsl	fraction of stability limit
Tmin	minimum expected temperature (C | F).
Tmax	maximum expected temperature (C | F).
Ti	initial temperature (C | F).
area	surface area (m^2 | ft^2).
mass	mass (kg | lb).
c	specific heat (kJ/(kg·K) | Btu/(lb·F)).
emit	emittance.
sig	if type=c, name of signal setting the temperature, type t.

This is a generic thermal mass. It may be used in place of surface and layer nodes. Its primary purpose is to allow the modeling of thin sheets of material which are exposed to air at both surfaces. This can be done by connecting two surface nodes with a material layer, but this inevitably requires the implicit solution for the node temperatures (see TEST1C). Thin, high conductivity masses can usually be adequately modeled by a single node, which is effectively assuming that the entire mass, including both surfaces, is at a uniform temperature.

This is expressed mathematically in terms of the Biot number: $Bi = hL/k$ where h is the average unit-surface conductance, L is a significant length dimension (obejct volume divided by surface area), and k the thermal conductivity of the solid body. In a thin plate mass the error in assuming that the internal temperature is uniform is less than 5% when $Bi < 10\%$ (Kreith, p 140, 1973).

The surface area may represent either one side or both sides of the mass, depending on how it is convectively and radiatively linked to other nodes.

The following values can be reported for mass nodes:

T	temperature - instantaneous, averaged.
Q	load - instantaneous, integrated, or averaged (for controlled node).

Reference:

Kreith, F., 1973, Principles of Heat Transfer, 3rd ed., Intext Educational Publishers.

ELEMENTS:

E.1 material layer:

element name mat L κ ρ c [R]

L	thickness of layer (m | ft).
κ	thermal conductivity (W/(m·K) | Btu/(h·ft·F)).
ρ	density (kg/m^3 | lb/ft^3).
c	specific heat (kJ/(kg·K) | Btu/(lb·F)).
R	if L, κ, ρ, or c = 0, thermal resistance (m^2·K/W | h·ft^2·F/Btu).

The material layer is used by the conduction link to connect surface and layer nodes. It defines the thermal properties of a conductive material.

These elements are used in TEST1A, TEST1B, TEST2A, and TEST2B.

E.2 controlled flow rate:

element name cfr flow

flow maximum mass flow rate (standard L/s | standard ft^3/min (cfm)).

All air flows in the present version of HLITE are specified using cfr elements and afp links to specify flows between air nodes.

Future extension: Use of additional elements as described in the AIRNET program to do relatively detailed combined air flow and heat transfer simulations.

E.3 variable convection coefficient:

<u>element</u> name <u>hcv</u> δ ϵ
α_+ β_+ γ_+ α_- β_- γ_-

δ ϵ coefficients for correlation: $h = \delta + \epsilon\surd J$.
α_+ β_+ γ_+ coefficients for correlation: $h = \alpha + \beta|\Delta T|^{\gamma}$.
α_- β_- γ_- + for $\Delta T>=0$, - for $\Delta T<0$ ($\Delta T = T_{srf} - T_{air}$).

The convection coefficients in real buildings varies with conditions and cannot be accurately represented by a single constant value. The variable convection coefficient element, <u>hcv</u>, is designed to allow consideration of the primary factors according to the most current correlations.

Simple natural convection model:

Most energy analysis programs base their simple natural convection models on data from ASHRAE [1]. This data includes the effect of surface slope. That is, when warm air is below a cooler horizontal surface (or cool air above a warm surface), there is more convective mixing than for air next to a vertical surface. Conversely, when cool air is below a warmer surface (or warm air above a cool surface) there is reduced convection. The values reported in Table 1, p 22.2 of [1] are for combined convection and radiation, so a radiative component of 1.02 times emissivity of 0.9 (English units) is subtracted from the tabluated values to give the following convection coefficients:

surface tilt	heat flow	h: $Btu/h \cdot ft^2 \cdot °F$	$W/m^2 \cdot K$
horizontal	enhanced	0.712	4.04
45°	enhanced	0.682	3.87
vertical	-	0.542	3.08
45°	reduced	0.402	2.28
horizontal	reduced	0.162	0.92

The second line of <u>hcv</u> data for a ceiling and a floor using the above data (English units) would be:
0.162 0.0 0.0 0.712 0.0 0.0, and
0.712 0.0 0.0 0.162 0.0 0.0, respectively, since the temperature difference is always based on surface temperature minus air temperature.

Detailed natural convection model.

A more detailed study of natural convection indicates that the convection coefficient is also a function of the magnitude of the temperature difference. ASHRAE presents two sets of values which could apply to detailed convection model. From page 3.12 of [1]:

surface tilt	heat flow	English	SI
horizontal	enhanced	$h = 0.22(\Delta T)^{.33}$	$h = 1.52(\Delta T)^{.33}$
vertical	-	$h = 0.19(\Delta T)^{.33}$	$h = 1.31(\Delta T)^{.33}$
horizontal	reduced	$h \approx 0.10(\Delta T)^{.33}$	$h \approx 0.70(\Delta T)^{.33}$

Convection coefficients for radiant heatind panels is given on page 7.2 of [2]:

surface tilt	heat flow	English	SI
horizontal	enhanced	$h = 0.32(\Delta T)^{.31}$	$h = 2.18(\Delta T)^{.31}$
vertical	-	$h = 0.26(\Delta T)^{.32}$	$h = 1.78(\Delta T)^{.32}$
horizontal	reduced	$h = 0.021(\Delta T)^{.25}$	$h = 0.14(\Delta T)^{.25}$

The second line of hcv data for a ceiling and a floor using the first set of values (English units) would be:
0.0 0.10 0.33 0.0 0.22 0.33, and
0.0 0.22 0.33 0.0 0.10 0.33, respectively.

Simple forced convection model:

The other primary factor effecting convection coefficients is the operation of the HVAC system forcing air through the room. One correlation for this case uses a combined convection and radiation coeffcient of 2.0 $\mathrm{Btu/h \cdot ft^2 \cdot {}^\circ F}$. This corresponds to a convection coefficient of 1.08 $\mathrm{Btu/h \cdot ft^2 \cdot {}^\circ F}$ or 6.14 $\mathrm{W/m^2 \cdot K}$, which gives a first line of ndf data (English units) like:
element name hcv 1.08 0.0 .

Detailed forced convection model:

A recent study by Spittler [3] on room convection coefficients at high flow rates found that the coefficients are dependent on the room/vent geometry and the momentum of the ventilation air. A correlation of the form

$$h = \delta + \epsilon \sqrt{J}$$

where J is the dimensionless jet momentum number is proposed.

$$J = FU / \rho g V$$

where
F = mass flow rate,
U = velocity of the air as it enters the room,
ρ = density of the ventilation air,
g = acceleration of gravity, and
V = room volume.
Letting A_e be the effective opening area of the air inlet, gives

$$\sqrt{J} = F / \rho\sqrt{gVA_e}$$

Spittler recommends the following correlations:

Ceiling inlet configuration (for $0.001 < J < 0.03$):

	$Btu/h \cdot ft^2 \cdot {}^\circ F$	$W/m^2 \cdot K$
ceiling	$h = 2.01 + 36.9 \sqrt{J}$	$h = 11.4 + 209.7 \sqrt{J}$
walls	$h = 0.74 + 14.3 \sqrt{J}$	$h = 4.2 + 81.3 \sqrt{J}$
floor	$h = 0.62 + 8.24 \sqrt{J}$	$h = 3.5 + 46.8 \sqrt{J}$

Side wall inlet configuration (for $0.001 < J < 0.03$, $Ar < 0.3$ (Archimedes Number))

	$Btu/h \cdot ft^2 \cdot {}^\circ F$	$W/m^2 \cdot K$
ceiling	$h = 0.11 + 10.5 \sqrt{J}$	$h = 0.6 + 59.4 \sqrt{J}$
walls	$h = 0.28 + 16.3 \sqrt{J}$	$h = 1.6 + 92.7 \sqrt{J}$
floor	$h = 0.56 + 7.75 \sqrt{J}$	$h = 3.2 + 44.0 \sqrt{J}$

The calculation of J requires the mass flow rate, room volume, and effective inlet area. These values are determined by the cnv link description.

notes:

If δ and ϵ are both set to 0, the natural convection corrrelation is used even when there is a system air flow.

See TEST5A for the simple convection models and TEST5B for the detailed convection models.

The algorithm implemented in HLITE does not check the limits for the forced convection correlation, since no other correlation outside those limits is available.

[1] 1989 ASHRAE Handbook - Fundamentals.
[2] 1987 ASHRAE Handbook - HVAC Systems and Applications.
[3] Spittler, J.D., "An Expiremental Investigation of Air FLow and Convective Heat Transfer in Enclosures Having Large Ventilative Flow Rates", PhD Thesis, University of Illinois, Urbana-Champaign, IL, 1990.

E.4 lamp:

element name lmp power light leff area emit mass c N
T_1 Q_1 L_1
...
T_N Q_N L_N

power	rated input power (W).
light	rated light output (lumen).
leff	luminous efficacy or radiated light (lumen/W).
area	surface area (m^2 | ft^2).
emit	emittance.
mass	mass (kg | lb).
c	average specific heat (kJ/(kg·K) | Btu/(lb·F)).
N	number of points used to define power and light curves.
Ti	minimum lamp wall temperature (C | F).
Qi	fraction of rated power at given temperature.
Li	fraction of rated light output at given temperature.

This is a model of a flourescent lamp. The rated input power ia for a simgle lamp and includes the power dissipated in the ballast. The luminous efficacy refers to the power contained in the radiated light. This is used in converting the rated light output from lumens to Watts for the calculation of various energy balances. This is not the standard definition of "luminous efficacy".

Area, mass, and specific heat are used for radiant and convective interchange and transient heat transfer analysis. Additional data must be included in the links and nodes that make up the complete description of the luminaire.

The characteristics of flourescent lamps are strongly dependent on the mercury vapor pressure within the lamp which in turn depends on the minimum lamp temperature. The following performance data was obtained from figure 8-34 of [1]

Tm_{in}	Q_i	L_i
0.0	0.661	0.022
20.0	0.672	0.068
40.0	0.704	0.165
60.0	0.818	0.476
70.0	0.894	0.701
80.0	0.971	0.865
90.0	0.999	0.960
100.0	0.965	0.995
120.0	0.858	0.850
140.0	0.721	0.697
215.0	0.000	0.000

This may be used as a reasonable approximation of flourescent lighting unless more specific data are available. These data are converted to a spline fit.
[1] IES Lighting Handbook, 1984 Reference Volume, Illumination Enginering Society of North America, New York, 1984.

E.5 equipment:

element name epq power area emit mass c

power	rated input power { W }.
area	surface area { m^2 | ft^2 }.
emit	emittance.
mass	mass { kg | lb }.
c	average specific heat { kJ/(kg·K) | Btu/(lb·F) }.

This is the generic equipment element. It describes a simgle unit of equipment; multiple units may be considered together under the equipment link command.

Area, emittance, mass, and specific heat are used for radiant and convective interchange and transient heat transfer analysis. Additional data must be included in the equipment link to complete description of the equipment.

LINKS:

L.1 Constant heat transfer coefficient:

link name knd K node1 node2

K coefficient value (W/K | Btu/(h·°F)).
node1 name of node 1.
node2 name of node 2.

This is a generic simple link. It can be used to connect any two nodes. Note that this link makes no reference to the surface areas of the nodes; its effect is included in the K value: $Q = K (T_1 - T_2)$. Similarly, there is no reference to the node mass; it must be specified elsewhere.

This link is used in TEST2D.

L.2 conduction link:

link name cnd element node1 node2

element	name of element, type mat.
node1	name of node 1, type lyr or srf.
node2	name of node 2, type lyr or srf.

The overall conductance is determined by the node areas and the mat element thermal properties: $K = A \kappa / L$.

The element properties are also used in determining the node heat capacities: $C = A L \rho c$. Half of C is assigned to each node.

The surface areas of the two nodes must be identical.

This link is used in TEST1A, TEST1B, TEST2A, and TEST2B.

L.3 constant convection link:

link name hcc hc node1 node2

hc	convection coefficient ($W/(m^2 \cdot K)$ | $Btu/(h \cdot ft^2 \cdot F)$).
node1	name of node 1, type srf or mas or eqp.
node2	name of node 2, type air.

The constant convection coefficient is a simple model which is primarily useful in HLITE test cases which can be solved analytically. Note that the node which describes a surface area must appear as node1, and node2 must be an air node. The heat transfer from the surface to the air is given by

$$Q = hc\ A\ (T_1 - T_2).$$

This link is used in TEST2A and TEST2B.

L.4 variable convection link:

link name cnv element node1 node2 link [VAe Fmax]

element	name of element, type hcv.
node1	name of node 1, type srf or mas or eqp.
node2	name of node 2, type air.
link	name of link giving a flow value, type afp.
VAe	room volume times effective area of flow opening (m^5 | ft^5), used to compute velocity from flow rate.
Fmax	maximum flow rate (standard L/s | standard ft^3/min (cfm)).

This links all the pieces necessary to describe a variable convection heat transfer. The appropriate hcv element must be used; there must be a node with a surface area and an air node; and the link must be describing an air flow unless the special link name null is used. A null link means that the flow rate portion of the hcv element is never used.

The VAe value is necessary to define the jet momentum number (section E.2) and Fmax is used in determining the maximum possible convection coefficient to evaluate stability. These values are included in the link data because they are room specific and some care must be used in defining values when there are multiple air inlets in the room or the room is described by multiple air nodes.

The following value can be reported for variable convection links:
h convection coefficient - instantaneous or averaged.

This link is used in TEST5A and TEST5B.

L.5 air flow path:

link name afp element node1 node2 sig

element	name of element, type cfr.
node1	name of node air flows from, type air
node2	name of node air flows to, type air
sig	name of signal point, type d.

The user is responsible for determining that a mass balance is maintained at each air node. This will later be replaced by a mass balance algorithm as used in the AIRNET program.

The following value can be reported for air flow path links:

F	mass flow rate - instantaneous or averaged.

L.6 radiant exchange link:

link name rad sF node1 node2

sF	(script F) view factor - include surface emissivity effects.
node1	name of node 1, type srf or mas or eqp.
node2	name of node 2, type srf or mas or eqp.

This is a simple radiation exchange model in which the effect of the emittances of both surfaces have been combined into the sF (script F) factor. Therefore, the emittance values given with the node data are not used. The user must insure that the data is consistant.

Two useful formulae [1] for the calculation of sF are:

(1) two infinitely large parallel plates:

$$sF = 1 / (1/\epsilon_1 + 1/\epsilon_2 - 1)$$

(2) two concentric spheres or cylinders:

$$sF = 1 / ((1-\epsilon_i)/\epsilon_i + 1 + A_1(1-\epsilon_2)/A_2\epsilon_2)$$

This link is used in TEST4A.

[1] Kreith, F., Principles of Heat Transfer, 3rd ed, Intext Education Publishers, New York, 1973, pp 260, 261.

L.7 view factor matrix super link:

link name vfm N
node1
F_{11} F_{12} ... F_{1N}
...
nodeN
F_{N1} F_{N2} ... F_{NN}

N	number of nodes (surfaces) in matrix.
nodei	name of node i, type srf or mas or eqp.
F_{ij}	view factor from surface i to surface j.

This link uses the view between a set of N surfaces, and the emittances given with the node data to compute the radiation interchange between the set of surfaces. The algorithm uses the view factors and emittances to compute script F view factors (described in section L.6). These are computationally more efficient that using an iteration to compute radiosities.

The sum of the view factors in each row should equal 1 (tested to ±1%) and reciprocity should apply: $A_i \cdot F_{ij} = A_j \cdot F_{ji}$ (tested to ±1%).

This data will be conveniently generated by the VLITE program.

This link is used in TEST4B.

L.8 luminaire super link:

```
link  name  lum  element  M  nodeE  offset
sig  balf  nodeB  N
node1  fr1
...
nodeN  frN
```

element	name of lamp element, type lmp.
M	lamp multiplier, i.e. number of lamps.
nodeE	name of equipment node, type eqp.
offset	average lamp temperature - minimum lamp temperature (C | F).
sig	name of signal point: fraction of rated wattage, type d.
balf	fraction of input energy to the ballast.
nodeB	if balf > 0, name of node containing the ballast, type mas; otherwise use null as a place holder.
N	number of nodes (surfaces) in light distribution matrix.
nodej	name of node j, type srf or mas or eqp.
frj	fraction of light from luminaire absorbed at surface.

The luminaire link is used to describe one or more luminaires. It describes multiple luminaires if they are subject to identical control: simply use a lamp multiplier and areas for the housing nodes that represent the combination of luminaires. See also the discussion of surface area in L.9.

A reasonable approximation for the offset value is that the minimum bulb temperature is 5°F (2.8°C) less than the average temperature.

The following value can be reported for luminaire links:

Q power used - instantaneous, integrated, or averaged.

This link is used in TEST6A and TEST6B.

L.9 equipment link:

link name eqp element N nodeE sig

element	name of lamp element, type eqp.
N	equipment multiplier.
nodeE	name of equipment node, type eqp.
sig	name of signal point: fraction of rated wattage, type d.

The equipment link is used to describe one or more pieces of equipment which release heat into the room. The equipment multiplier assigns a multiple of the element area and thermal mass to the node.

The equipment node can be linked to the room air by convection and to other surfaces by radiant interchange. Equipment with cooling fans may require very high convection coefficients for accurate modeling. The calculation of these links requires a node surface area, which is defined by the equipment link instead of at the equipment node. Therefore, the equipment link must be defined before any other links to the equipment node. Failure to do so results in an error message.

Note: It would have been possible to define the equipment surface area in the equipment node, but it seems easier to define the equipment area in one place (the element data) and let the multiplier insure consistancy of mass and area values.

This link is used in TEST6C.

CONTROLS: (not yet implemented)

C.1 temperature sensor:

control name ts node out scale offset

node	name of node for sensed temperature.
out	name of output signal, type d.

output = scale * (Tnode - offset) to give a value between 0 and 1.

C.2 flow rate sensor:

control name fs link out scale offset

link	name of link for sensed flow, type afp.
out	name of output signal, type d.

C.3 set temperature:

control name st in out scale offset

in	name of input signal, type d.
out	name of output signal, type t.

C.4 signal inverter:

control name inv in out

in	name of input signal, type d.
out	name of output signal (out = 1.0 - in), type d.

C.5 proportional-integral control:

control name pic in out set kp ki

in	name of input signal, type d.
out	name of output signal, type d.
set	name of set point signal, type d.
kp	proportional factor
ki	integral factor

? upper limit control:

control name ulc in out limit

in	name of input signal, type d.
out	name of output signal, type d.
limit	name of upper limit signal, type d.

TIME SCALES:

```
times  nr  t1  t2  ..  tn

   nr    number of different time steps
   t1 ... tn   shortest to longest step (in seconds)
```

Each successively longer time step must be a simple multiple of the previous time step. One hour (3600 sec) must be a simple multiple of the longest time step.

examples:

```
times  5  12   60  300  1200  3600
times  3  60  180  900
times  1  60
```

The full impact of using multiple time scales has not been established.

REPORTS:

```
report   file   N   incr
type1   name   value   action   format
...
typeN   name   value   action   format
```

file	name defining this report, an MS-DOS file name (no \'s).
N	number of items reported.
incr	time increment between reports (sec).
typej	node, link, or signal.
name	identifies which one.
value	selects the value to be reported.
action	i = instantaneous value, s = integrated (trapezoidal) value, a = averaged value.
format	C langauge format specifier, e.g. %8.3f or %12.5e .

The time step must be defined before reports are defined.

There is a danger of misidentifying this input if N does not exactly match the number of lines that follow.

Each report is written to a different file. The file name should include no backslashes, '\'. The maximum number of reports is 5, which is set by the parameter MAXRPTFL (in the source code).

This output can be modified for direct import to spreadsheet programs by one of the interactive execution control parameters. In that case it may also be desirable to eliminate blanks from the report file, which can be done by changing the format specifiers, e.g. %.3f or %.5e .

Future extension: Reports that can also be activated from the DEF. This would allow printing of values at irregular intervals or for just a few time steps during the simulation.

```
display   N   incr
type1   name   value   action   format
...
typeN   name   value   action   format
```

This defines the values displayed at the bottom of the screen during simulation. The input is similar to that for reports (except no file name is needed).

Boundary Values File (BVF)

The BVF sets node values. The first record of the boundary values file tells the number of values in each record. The second record gives the names of the nodes corresponding to the respective values. The remaining records give a time and the values for that time. During simulation, values at intermediate times are obtained by linear interpolation. The BVF determines simulation start and stop times.

Consider the following BVF (file TEST1B.BVF):

```
1
node-5
001/00:00:00  50.0
001/01:00:00  50.0
001/02:00:00  32.0
001/03:00:00  50.0
001/06:00:00  50.0
*
```

The 1 on the first line indicates that each line of data will report one value, the temperature of node-5 as indicated on the second line, which was also identified as a boundary value node in the NDF. The BVF indicates that this temperature is constant for the first hour, decreases to 32°F at the end of the second hour, returns to 50°F during the next hour, and remains at that value until the end of simulation. Note that the time between data points is arbitrary. The times set the total period of simulation to six hours.

The * on the last line indicates the end of BVF information. This is the same as for the NDF. Also similar is the use of a / in the first column to indicate a comment and the interpretation of data past the last required entry on a line as a comment.

Times indicated by:

day number /	3 digits, 000 to 999
hour :	2 digits, 00 to 23
minute :	2 digits, 00 to 59
second	2 digits, 00 to 59

Discrete Events File (DEF)

The DEF sets signal values. This allows the changing of set points, etc., according to a very general user-defined schedule.

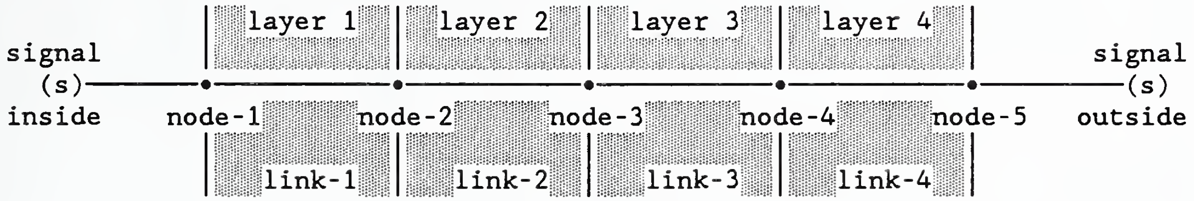
The following contents of TEST1B.DEF indicate that the control signal named "inside" is set to 77°F for one hour and then returned to 68°F, which is its initial value as specified in the NDF.

```
001/00:00:00
001/04:00:00  inside  77.0
001/05:00:00  inside  68.0
002/00:00:00
*
```

A single time equal to or greater than the final BVF time is required. Other times outside the simulation period specified by the BVF are ignored.

APPENDIX B: Analytic Test Cases

TEST1A involves the simplest heat transfer simulation, conduction within a homogeneous wall divided into 4 layers as shown.



There are 2 temperature signals which specify the temperatures at nodes 1 and 5. The nodes are all of the same type, lyr, with initial temperature of 68°F or 50°F, and areas of 10 ft^2. Nodes 1 and 5 are controlled, c, by the specified signal points, inside and outside. The material layers represent 1 inch of a masonry material ($\kappa = 0.45$, $\rho = 120.$, and $c = 0.20$). The five nodes are linked by the four material layers.

This is described in the following Network Data File:

```
signal inside t 68.
signal outside t 50.

node node-1 lyr c 1.0 68. 68. 68. 10. inside
node node-2 lyr v 1.0 50. 68. 68. 10.
node node-3 lyr v 1.0 50. 68. 68. 10.
node node-4 lyr v 1.0 50. 68. 68. 10.
node node-5 lyr c 1.0 50. 50. 50. 10. outside

element masonry-1" mat 0.083333 0.45 120. 0.2

link link-1 cnd masonry-1" node-1 node-2
link link-2 cnd masonry-1" node-2 node-3
link link-3 cnd masonry-1" node-3 node-4
link link-4 cnd masonry-1" node-4 node-5

times 1 300

report test1a.rpt  7  600
node  node-1  T  i  %8.4f
node  node-2  T  i  %8.4f
node  node-3  T  i  %8.4f
node  node-4  T  i  %8.4f
node  node-5  T  i  %8.4f
node  node-1  Q  a  %12.5e
node  node-5  Q  a  %12.5e

display  2  300
node  node-2  T  i  %8.4f
node  node-4  T  i  %8.4f

* end of data
```

The NDF indicates that transient simulation will be done with a 300 second (5 minute) time step. The temperatures for all the nodes and the loads at the controlled nodes are written to a file named "test1a.rpt" at every other time step. During the simulation, a line at the bottom of the screen is updated every (in this case) time step. This line gives the simulated time, the actual time since the simulation began, and the temperatures of nodes 2 and 4.

The contents of the BVF for this test are:

```
0
001/00:00:00
001/08:00:00
```

and the contents of the DEF are:

```
001/00:00:00
001/24:00:00
```

The BVF causes simulation for 8 hours; the DEF indicates no changes in the control signals.

The results of the simulation are given in file test1a.rpt:

```
001/00:00:00  68.0000 68.0000 68.0000 68.0000 50.0000  0.0000e+00  0.0000e+00
001/00:10:00  68.0000 68.0000 67.0887 61.7225 50.0000  0.0000e+00 -6.7433e+02
001/00:20:00  68.0000 67.4567 65.1671 59.2802 50.0000  2.7680e+00 -6.4378e+02
001/00:30:00  68.0000 66.6655 63.6523 57.9147 50.0000  3.0078e+01 -5.0449e+02
001/00:40:00  68.0000 65.9421 62.5070 57.0175 50.0000  7.1784e+01 -4.2891e+02
001/00:50:00  68.0000 65.3578 61.6434 56.3806 50.0000  1.1064e+02 -3.7980e+02
001/01:00:00  68.0000 64.9055 60.9925 55.9124 50.0000  1.4223e+02 -3.4512e+02
001/01:10:00  68.0000 64.5610 60.5019 55.5631 50.0000  1.6674e+02 -3.1967e+02
001/01:20:00  68.0000 64.3002 60.1321 55.3008 50.0000  1.8543e+02 -3.0070e+02
001/01:30:00  68.0000 64.1033 59.8533 55.1035 50.0000  1.9958e+02 -2.8646e+02
001/01:40:00  68.0000 63.9548 59.6432 54.9548 50.0000  2.1026e+02 -2.7575e+02
001/01:50:00  68.0000 63.8428 59.4848 54.8428 50.0000  2.1832e+02 -2.6769e+02
001/02:00:00  68.0000 63.7584 59.3654 54.7584 50.0000  2.2440e+02 -2.6161e+02
...
...
...
001/07:40:00  68.0000 63.5000 59.0000 54.5000 50.0000  2.4300e+02 -2.4300e+02
001/07:50:00  68.0000 63.5000 59.0000 54.5000 50.0000  2.4300e+02 -2.4300e+02
001/08:00:00  68.0000 63.5000 59.0000 54.5000 50.0000  2.4300e+02 -2.4300e+02
```

This output shows gradual change in the temperature distribution to the expected values. The computed loads, 243 Btu/h, are also correct.

$$Q = \kappa\ A\ \Delta T\ /\ L = 0.45 * 10. * 18.\ /\ 0.333 = 243.$$

TEST1B is a quick test of the implicit method of calculation and the operation of the BVF and DEF. It uses the same thermal network as TEST1A, but the layers have no mass. Therefore, there are no transients in the solution.

```
signal inside t 68.

node node-1 lyr c 1. 68. 68. 68. 10. inside
node node-2 lyr v 1. 50. 68. 68. 10.
node node-3 lyr v 1. 50. 68. 68. 10.
node node-4 lyr v 1. 50. 68. 68. 10.
node node-5 lyr b 1. 50. 50. 50. 10.

element masonry-1" mat 0.083333 0.45 120. 0.0 0.0  no thermal mass

link link-1 cnd masonry-1" node-1 node-2
link link-2 cnd masonry-1" node-2 node-3
link link-3 cnd masonry-1" node-3 node-4
link link-4 cnd masonry-1" node-4 node-5

times 1 900

report test1b.rpt  7  900
node  node-1  T  i  %8.4f
node  node-2  T  i  %8.4f
node  node-3  T  i  %8.4f
node  node-4  T  i  %8.4f
node  node-5  T  i  %8.4f
node  node-1  Q  i  %12.5e
node  node-1  Q  s  %12.5e

display  3  900
node  node-2  T  i  %8.4f
node  node-4  T  i  %8.4f
node  node-5  T  i  %8.4f

* end of data
```

The following data is in TEST1B.BVF:

```
1
node-5
001/00:00:00  50.0
001/01:00:00  50.0
001/02:00:00  32.0
001/03:00:00  50.0
001/06:00:00  50.0
*
```

This indicates that each line of data will report one value, the temperature of node-5, which was also identified as a boundary value node in the NDF. The BVF indicates that this temperature is constant for the first hour, decreases to 32°F at the end of the second hour, returns to 50°F during the next hour, and remains at that value until the end of simulation. Note that the time between data points is arbitrary.

The following contents of TEST1B.DEF indicate that the control signal "inside" is set to 77°F for one hour and then returned to 68°F, which is its initial value as specified in the NDF.

```
001/00:00:00
001/04:00:00  inside  77.0
001/05:00:00  inside  68.0
002/00:00:00
```

The following report file was generated:

```
001/00:00:00  68.0000 68.0000 68.0000 68.0000 50.0000  0.0000e+00  0.0000e+00
001/00:15:00  68.0000 63.5000 59.0000 54.5000 50.0000  2.4300e+02  3.0375e+01
001/00:30:00  68.0000 63.5000 59.0000 54.5000 50.0000  2.4300e+02  6.0750e+01
001/00:45:00  68.0000 63.5000 59.0000 54.5000 50.0000  2.4300e+02  6.0750e+01
001/01:00:00  68.0000 63.5000 59.0000 54.5000 50.0000  2.4300e+02  6.0750e+01
001/01:15:00  68.0000 62.3750 56.7500 51.1250 45.5000  3.0375e+02  6.8344e+01
001/01:30:00  68.0000 61.2500 54.5000 47.7500 41.0000  3.6450e+02  8.3532e+01
001/01:45:00  68.0000 60.1250 52.2500 44.3750 36.5000  4.2525e+02  9.8719e+01
001/02:00:00  68.0000 59.0000 50.0000 41.0000 32.0000  4.8600e+02  1.1391e+02
001/02:15:00  68.0000 60.1250 52.2500 44.3750 36.5000  4.2525e+02  1.1391e+02
001/02:30:00  68.0000 61.2500 54.5000 47.7500 41.0000  3.6450e+02  9.8719e+01
001/02:45:00  68.0000 62.3750 56.7500 51.1250 45.5000  3.0375e+02  8.3532e+01
001/03:00:00  68.0000 63.5000 59.0000 54.5000 50.0000  2.4300e+02  6.8344e+01
001/03:15:00  68.0000 63.5000 59.0000 54.5000 50.0000  2.4300e+02  6.0750e+01
001/03:30:00  68.0000 63.5000 59.0000 54.5000 50.0000  2.4300e+02  6.0750e+01
001/03:45:00  68.0000 63.5000 59.0000 54.5000 50.0000  2.4300e+02  6.0750e+01
001/04:00:00  77.0000 63.5000 59.0000 54.5000 50.0000  7.2900e+02  1.2150e+02
001/04:15:00  77.0000 70.2500 63.5000 56.7500 50.0000  3.6450e+02  1.3669e+02
001/04:30:00  77.0000 70.2500 63.5000 56.7500 50.0000  3.6450e+02  9.1125e+01
001/04:45:00  77.0000 70.2500 63.5000 56.7500 50.0000  3.6450e+02  9.1125e+01
001/05:00:00  68.0000 70.2500 63.5000 56.7500 50.0000 -1.2150e+02  3.0375e+01
001/05:15:00  68.0000 63.5000 59.0000 54.5000 50.0000  2.4300e+02  1.5188e+01
001/05:30:00  68.0000 63.5000 59.0000 54.5000 50.0000  2.4300e+02  6.0750e+01
001/05:45:00  68.0000 63.5000 59.0000 54.5000 50.0000  2.4300e+02  6.0750e+01
001/06:00:00  68.0000 63.5000 59.0000 54.5000 50.0000  2.4300e+02  6.0750e+01
    time         T1      T2      T3      T4      T5        Q1          Q1
```

Note the loads at time 4:00:00 and 5:00:00 which include the power required to change the temperatures. This is caused by the time stepping shceme. The temperature of the node has been set to the control values but the load is based on the temperature at the start of the time step.

Note instantaneous loads and total energy for each quarter hour time step.

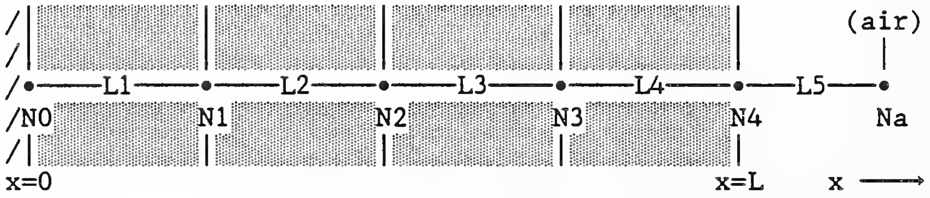
TEST1C

TEST1C tests the simulation of a thin layer. Earlier tests indicated that this requires a direct solution of implicit (simultaneous) equations. Convergence is very slow for an iterative solution.

```
signal inside t 68.
signal outside t 50.

node node-1 air c 1. 68. 68. 68. 100. inside  inside
node node-2 srf v 1. 50. 68. 68. 10.  0.90
node node-3 srf v 1. 50. 68. 68. 10.  0.90
node node-4 air c 1. 50. 50. 50. 100. outside outside

element metal mat 0.0052 118. 169. 0.21

link link-1 hcc  1.0  node-2 node-1
link link-2 cnd metal node-2 node-3
link link-3 hcc  1.0  node-3 node-4

times 1 300

report test1c.rpt  6  600
node  node-1  T  i  %8.3f
node  node-2  T  i  %8.3f
node  node-3  T  i  %8.3f
node  node-4  T  i  %8.3f
node  node-1  Q  i  %9.3f
node  node-4  Q  i  %9.3f

display  3  300
node  node-1  T  i  %8.3f
node  node-2  T  i  %8.3f
node  node-4  T  i  %8.3f

* end of data
```

```
001/00:00:00   68.000  68.000  68.000  50.000    0.000    0.000
001/00:10:00   68.000  61.485  61.485  50.000   42.707 -137.289
001/00:20:00   68.000  59.686  59.686  50.000   76.941 -103.055
001/00:30:00   68.000  59.190  59.189  50.000   86.393  -93.603
001/00:40:00   68.000  59.053  59.052  50.000   89.003  -90.993
001/00:50:00   68.000  59.015  59.014  50.000   89.723  -90.273
001/01:00:00   68.000  59.004  59.004  50.000   89.922  -90.074
001/01:10:00   68.000  59.001  59.001  50.000   89.977  -90.019
001/01:20:00   68.000  59.001  59.000  50.000   89.992  -90.004
001/01:30:00   68.000  59.000  59.000  50.000   89.996  -90.000
001/01:40:00   68.000  59.000  59.000  50.000   89.998  -89.998
001/01:50:00   68.000  59.000  59.000  50.000   89.998  -89.998
001/02:00:00   68.000  59.000  59.000  50.000   89.998  -89.998
```

TEST2A checks the simulation of transient conduction within a homogeneous wall. The physical problem consists of an infinite flat plate starting at temperature T_i which is suddenly exposed to fluid at temperature T_∞. The HLITE model of the wall consists of 4 identical layers:



By linking node-0 only to node-1, there is no heat transfer across the x=0 plane. This equivalent to a plate of thickness 2L exposed to the fluid at both faces. This is done in the following NDF:

```
signal air-temp t 0.0

node node-0 lyr v 1. 0. 100. 0.0 10.
node node-1 lyr v 1. 0. 100. 0.0 10.
node node-2 lyr v 1. 0. 100. 0.0 10.
node node-3 lyr v 1. 0. 100. 0.0 10.
node node-4 srf v 1. 0. 100. 0.0 10.  .90
node node-a air c 1. 0. 100. 0.0 100.  air-temp air-temp

element masonry-0.75" mat 0.0625 0.45 120. 0.2

link link-1 cnd masonry-0.75" node-0 node-1
link link-2 cnd masonry-0.75" node-1 node-2
link link-3 cnd masonry-0.75" node-2 node-3
link link-4 cnd masonry-0.75" node-3 node-4
link link-5 hcc  1.0          node-4 node-a

times 1 120

report test2a.rpt  4  120
node   node-a  T  i  %8.4f
node   node-4  T  i  %8.4f
node   node-0  T  i  %8.4f
node   node-a  Q  i  %12.5e

report test2a.sum  1  3600
node   node-a  Q  s  %12.5e

display  3  120
node   node-a  T  i  %8.4f
node   node-4  T  i  %8.4f
node   node-0  T  i  %8.4f

* end of data
```

TEST2A uses the following BVF:

```
0
000/23:00:00
001/06:00:00
```

and the following DEF:

```
001/00:00:00
001/00:00:00  air-temp  100.0
002/00:00:00
```

to compute the following reported values:

```
000/23:00:00  -0.0000 -0.0000 -0.0000  0.0000e+00
 ...
000/23:58:00  -0.0000 -0.0000 -0.0000  0.0000e+00
001/00:00:00 100.0000 -0.0000 -0.0000  5.4127e+03
001/00:02:00 100.0000  4.4444 -0.0000  1.0000e+03
001/00:04:00 100.0000  7.2691 -0.0000  9.5556e+02
001/00:06:00 100.0000  9.2919 -0.0000  9.2731e+02
001/00:08:00 100.0000 10.8769 -0.0000  9.0708e+02
001/00:10:00 100.0000 12.1972  0.0058  8.9123e+02
001/00:12:00 100.0000 13.3419  0.0254  8.7803e+02
001/00:14:00 100.0000 14.3609  0.0656  8.6658e+02
001/00:16:00 100.0000 15.2845  0.1315  8.5639e+02
001/00:18:00 100.0000 16.1324  0.2257  8.4716e+02
001/00:20:00 100.0000 16.9186  0.3491  8.3868e+02
001/00:22:00 100.0000 17.6529  0.5015  8.3081e+02
001/00:24:00 100.0000 18.3432  0.6816  8.2347e+02
001/00:26:00 100.0000 18.9953  0.8877  8.1657e+02
001/00:28:00 100.0000 19.6140  1.1179  8.1005e+02
001/00:30:00 100.0000 20.2035  1.3699  8.0386e+02
001/00:32:00 100.0000 20.7670  1.6419  7.9797e+02
 ...
001/01:00:00 100.0000 27.0200  6.6457  7.3363e+02
 ...
001/02:00:00 100.0000 36.8839 18.5749  6.3414e+02
 ...
001/03:00:00 100.0000 45.1663 29.2346  5.5091e+02
 ...
001/04:00:00 100.0000 52.3527 38.5081  4.7871e+02
 ...
001/05:00:00 100.0000 58.5970 46.5667  4.1597e+02
 ...
001/06:00:00 100.0000 64.0229 53.5692  3.6146e+02
    time         Ta       T4       T0        Qa
```

The step change in temperature for 0°F to 100°F is chosen for easy comparison to the normalized temperatures of the analytic solution for this case. The stability analysis done by HLITE indicates stability limits of about 330 seconds for the surface node and 375 seconds for the interior nodes. The 120 second time step causes HLITE to use the explicit time integration method.

The computed values can be compared to the classical analytic solution:

$$\frac{T(x,t) - T_\infty}{T_i - T_\infty} = \sum_{n=1}^{\infty} e^{-\delta_n^2 (t\alpha/L^2)} \; 2 \; \frac{\sin\delta_n \cos(\delta_n x/L)}{\delta_n + \sin\delta_n \cos\delta_n}$$

with

$$\delta_n \tan\delta_n = hL/\kappa$$

The following results were computed (using program HEATSTEP) for the test case using normalized temperatures of $T_i = 0$ and $T_\infty = 1$.

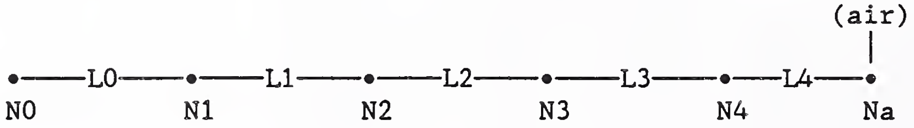
time	T at L	T at 0
00:00:00	0.000000	0.000000
00:00:10	0.017842	0.000000
00:00:20	0.025086	0.000000
00:00:30	0.030588	0.000000
00:00:40	0.035188	0.000000
00:00:50	0.039213	0.000000
00:01:00	0.042828	0.000000
00:01:10	0.046134	0.000000
00:01:20	0.049195	0.000000
00:01:30	0.052056	0.000000
00:01:40	0.054749	0.000000
00:01:50	0.057299	0.000000
00:02:00	0.059726	0.000000
00:02:30	0.066402	0.000000
00:03:00	0.072374	0.000000
00:03:30	0.077811	0.000000
00:04:00	0.082828	0.000000
00:04:30	0.087500	0.000000
00:05:00	0.091884	0.000000
00:06:00	0.099949	0.000003
00:07:00	0.107265	0.000011
00:08:00	0.113990	0.000031
00:09:00	0.120233	0.000072
00:10:00	0.126073	0.000143
00:12:00	0.136772	0.000415
00:14:00	0.146426	0.000909
00:16:00	0.155257	0.001670
00:18:00	0.163418	0.002718
00:20:00	0.171021	0.004057
00:22:00	0.178151	0.005680
00:24:00	0.184872	0.007574
00:26:00	0.191239	0.009718
00:28:00	0.197293	0.012093
00:30:00	0.203072	0.014679
00:32:00	0.208604	0.017453
00:34:00	0.213918	0.020398
00:36:00	0.219034	0.023495
00:38:00	0.223973	0.026727
00:40:00	0.228753	0.030078
00:42:00	0.233388	0.033535
00:44:00	0.237893	0.037084
00:46:00	0.242279	0.040715
00:48:00	0.246558	0.044417
00:50:00	0.250738	0.048180
00:52:00	0.254829	0.051997
00:54:00	0.258838	0.055859
00:56:00	0.262772	0.059760
00:58:00	0.266637	0.063694
01:00:00	0.270440	0.067655
01:10:00	0.288662	0.087718
01:20:00	0.305872	0.107921
01:30:00	0.322342	0.128005
01:40:00	0.338234	0.147827
01:50:00	0.353644	0.167309
02:00:00	0.368634	0.186409
02:10:00	0.383239	0.205109
02:20:00	0.397485	0.223399
02:30:00	0.411390	0.241281
02:40:00	0.424968	0.258759
02:50:00	0.438227	0.275838
03:00:00	0.451179	0.292526
03:10:00	0.463831	0.308830
03:20:00	0.476190	0.324760
03:30:00	0.488265	0.340323
03:40:00	0.500060	0.355528
03:50:00	0.511583	0.370382
04:00:00	0.522841	0.384894
04:10:00	0.533839	0.399071
04:20:00	0.544584	0.412922
04:30:00	0.555081	0.426454
04:40:00	0.565336	0.439674
04:50:00	0.575355	0.452589
05:00:00	0.585142	0.465206
05:10:00	0.594704	0.477533
05:20:00	0.604046	0.489575
05:30:00	0.613173	0.501340
05:40:00	0.622089	0.512834
05:50:00	0.630799	0.524062
06:00:00	0.639309	0.535032
∞	1.000000	1.000000

TEST2B is a test of the implicit time integration method. It differs from the explicit test only in the size of the time step, which is set at 600 seconds.

```
000/23:00:00  -0.0000 -0.0000 -0.0000  0.0000e+00
 ...
000/23:50:00  -0.0000 -0.0000 -0.0000  0.0000e+00
001/00:00:00 100.0000 -0.0000 -0.0000  1.0825e+03
001/00:10:00 100.0000  9.7860  0.2744  1.0000e+03
001/00:20:00 100.0000 15.2648  0.9635  9.0214e+02
001/00:30:00 100.0000 18.9949  2.0556  8.4735e+02
001/00:40:00 100.0000 21.8838  3.4685  8.1005e+02
001/00:50:00 100.0000 24.3047  5.1083  7.8116e+02
001/01:00:00 100.0000 26.4364  6.8947  7.5695e+02
 ...
001/02:00:00 100.0000 36.5881 18.3097  6.4925e+02
 ...
001/03:00:00 100.0000 44.8416 28.8263  5.6449e+02
 ...
001/04:00:00 100.0000 51.9811 38.0295  4.9141e+02
 ...
001/05:00:00 100.0000 58.1934 46.0459  4.2783e+02
 ...
001/06:00:00 100.0000 63.6017 53.0256  3.7248e+02
```

General note: The finite difference method is actually solving a slightly different problem than the step change in air temperature. The change in temperature cannot be instantaneous; it occurs over a single time step. That is, during one time step the air temparature changes linearly from its initial to its final value. Shorter time steps are better at representing a step change, but they never really produce a step change.

TEST2C checks the mas elements and knd links in a transient simulation which is identical to TEST2A. The comfiguration of nodes and links remains the same. The must be computed to match the corresponding mat elements and lyr links.

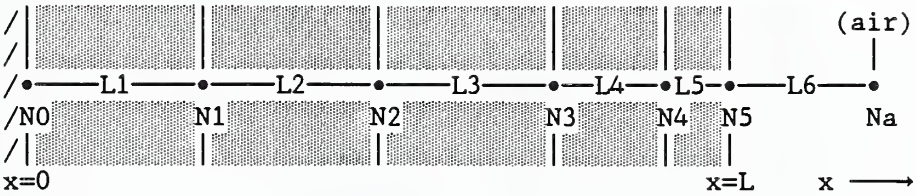


The masses of nodes 1, 2, and 3 are given by $m = \rho LA = 120.\cdot 0.0625\cdot 10. = 75.$ Nodes 0 and 4 have half that mass. The heat transfer coefficient between nodes is given by $K = \kappa A/L = 0.45\cdot 10./0.025 = 72.$ These values are used in the following NDF:

```
signal air-temp t 0.0

node node-0 mas v 1. 0. 100. 0.0 10. 37.5 0.2 .90
node node-1 mas v 1. 0. 100. 0.0 10. 75.0 0.2 .90
node node-2 mas v 1. 0. 100. 0.0 10. 75.0 0.2 .90
node node-3 mas v 1. 0. 100. 0.0 10. 75.0 0.2 .90
node node-4 mas v 1. 0. 100. 0.0 10. 37.5 0.2 .90
node node-a air c 1. 0. 100. 0.0 100.  air-temp air-temp

link link-1 knd  72.0  node-0 node-1
link link-2 knd  72.0  node-1 node-2
link link-3 knd  72.0  node-2 node-3
link link-4 knd  72.0  node-3 node-4
link link-5 hcc  1.0   node-4 node-a

times 1 120
 ...
```

This test gives results identical to TEST2A.

TEST2D tests the use of multiple time steps. The surface layer of TEST2A is divided into two layers.



```
signal air-temp t 0.0

node node-0 lyr v 1. 0. 100. 0.0 10.
node node-1 lyr v 1. 0. 100. 0.0 10.
node node-2 lyr v 1. 0. 100. 0.0 10.
node node-3 lyr v 1. 0. 100. 0.0 10.
node node-4 lyr v 1. 0. 100. 0.0 10.
node node-5 srf v 1. 0. 100. 0.0 10.   .90
node node-a air c 1. 0. 100. 0.0 100.  air-temp air-temp

element masonry-0.25" mat 0.02083 0.45 120. 0.2
element masonry-0.50" mat 0.04167 0.45 120. 0.2
element masonry-0.75" mat 0.0625 0.45 120. 0.2

link link-1 cnd masonry-0.75" node-0 node-1
link link-2 cnd masonry-0.75" node-1 node-2
link link-3 cnd masonry-0.75" node-2 node-3
link link-4 cnd masonry-0.50" node-3 node-4
link link-5 cnd masonry-0.25" node-4 node-5
link link-6 hcc  1.0          node-5 node-a

times 3  30 60 120
 ...
```

These times were chosen to allow comparison to the TEST2A results and to match the stability limits of the thinner layers. This is reported in TEST2D.OUT:

```
 ...
node:  node-3    C = 12.50 Btu/F    node # 4
   linked to node-4             by link-4            K = 107.99 Btu/(hr*F)
   linked to node-2             by link-3            K = 72.00 Btu/(hr*F)
   sum(K) = 179.99   stability limit = 250.0 sec   time step = 120

node:  node-4    C = 7.50 Btu/F    node # 5
   linked to node-5             by link-5            K = 216.03 Btu/(hr*F)
   linked to node-3             by link-4            K = 107.99 Btu/(hr*F)
   sum(K) = 324.03   stability limit = 83.3 sec   time step = 60

node:  node-5    C = 2.50 Btu/F    node # 6
   linked to node-a             by link-6            K = 10.0 Btu/(hr*F)
   linked to node-4             by link-5            K = 216.03 Btu/(hr*F)
   sum(K) = 226.03   stability limit = 39.8 sec   time step = 30
 ...
```

The results of simulation are reported at the same times used in TEST2A:

```
000/23:00:00  -0.0000 -0.0000 -0.0000  0.0000e+00
 ...
000/23:58:00  -0.0000 -0.0000 -0.0000  0.0000e+00
001/00:00:00 100.0000 -0.0000 -0.0000  2.1651e+04
001/00:02:00 100.0000  5.1262 -0.0000  9.5642e+02
001/00:04:00 100.0000  7.6559 -0.0000  9.2858e+02
001/00:06:00 100.0000  9.4215 -0.0000  9.0973e+02
001/00:08:00 100.0000 10.8447 -0.0000  8.9485e+02
001/00:10:00 100.0000 12.0689  0.0047  8.8220e+02
001/00:12:00 100.0000 13.1570  0.0217  8.7102e+02
001/00:14:00 100.0000 14.1425  0.0582  8.6094e+02
001/00:16:00 100.0000 15.0464  0.1193  8.5171e+02
001/00:18:00 100.0000 15.8833  0.2080  8.4319e+02
001/00:20:00 100.0000 16.6637  0.3254  8.3525e+02
001/00:22:00 100.0000 17.3958  0.4714  8.2782e+02
001/00:24:00 100.0000 18.0862  0.6450  8.2082e+02
001/00:26:00 100.0000 18.7400  0.8445  8.1420e+02
001/00:28:00 100.0000 19.3615  1.0680  8.0790e+02
001/00:30:00 100.0000 19.9543  1.3135  8.0191e+02
 ...
001/01:00:00 100.0000 26.8301  6.5212  7.3266e+02
 ...
001/02:00:00 100.0000 36.7421 18.4331  6.3332e+02
 ...
001/03:00:00 100.0000 45.0434 29.1072  5.5021e+02
 ...
001/04:00:00 100.0000 52.2447 38.3955  4.7811e+02
 ...
001/05:00:00 100.0000 58.5020 46.4673  4.1547e+02
 ...
001/06:00:00 100.0000 63.9393 53.4815  3.6103e+02
```

These results compare extremely well to the analytic solution. In addition this simulation is computing temperatures at the surface node every 30 seconds which would be useful for the analysis of dynamics at that time scale.

The following table summarizes the transient conduction tests.

Surface temperatures:

time	analytic	test2a	test2b	test2d
00:02:00	0.059726	0.044444	-	0.051262
00:04:00	0.082828	0.072691	-	0.076559
00:10:00	0.126073	0.121972	0.097860	0.120689
01:00:00	0.270440	0.270200	0.264364	0.268301
02:00:00	0.368634	0.368839	0.365881	0.367421
06:00:00	0.639309	0.640229	0.636017	0.639393
execution time (sec): (without reports)		0.93	0.82	2.53

TEST3A checks the operation of air node controls when both signals are identical. The network consists of a single air node controlled by a single signal which causes a step change in temperature during the simulation. This also provides test of a degenerate network.

```
signal air-temp t 50.

node node-a air c 1. 50. 68. 50. 100.  air-temp air-temp

times 1 900

report test1d.rpt  4  900
node  node-a  T  i  %8.4f
node  node-a  Q  i  %12.5e        )
node  node-a  Q  a  %12.5e        } Note 3 different reporting methods
node  node-a  Q  s  %12.5e        )

report test3A.sum  1  3600
node  node-a  Q  s  %12.5e

display  2  900
node  node-a  T  i  %8.4f
node  node-a  Q  i  %12.5f

* end of data
```

The BVF allows for two hours of simulation. The DEF causes the airtemperature to increase to 68°F after one hour:

```
001/01:00:00   air-temp   68.
```

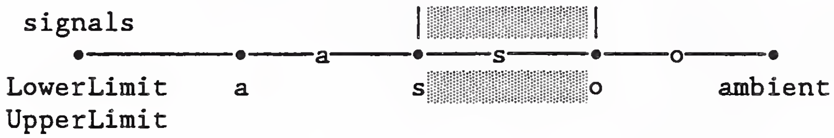
The resulte from TEST3A.RPT are:

```
001/00:00:00  50.0000  0.0000e+00  0.0000e+00  0.0000e+00
001/00:15:00  50.0000  0.0000e+00  0.0000e+00  0.0000e+00
001/00:30:00  50.0000  0.0000e+00  0.0000e+00  0.0000e+00
001/00:45:00  50.0000  0.0000e+00  0.0000e+00  0.0000e+00
001/01:00:00  68.0000  1.2990e+02  6.4952e+01  1.6238e+01
001/01:15:00  68.0000  0.0000e+00  6.4952e+01  1.6238e+01
001/01:30:00  68.0000  0.0000e+00  0.0000e+00  0.0000e+00
001/01:45:00  68.0000  0.0000e+00  0.0000e+00  0.0000e+00
001/02:00:00  68.0000  0.0000e+00  0.0000e+00  0.0000e+00
```

The resulte from TEST3A.SUM are:

```
001/00:00:00   0.0000e+00
001/01:00:00   1.6238e+01
001/02:00:00   1.6238e+01
```

TEST3B checks the operation of air node dead band control operation. There are two unconnected thermal networks in this test. Simple convection and conduction links (overall U = 0.10 Btu/h·ft^2·°F) connect the two air nodes to a boundary node representing ambient air. One of the air nodes is simulated with mass; the other is massless.

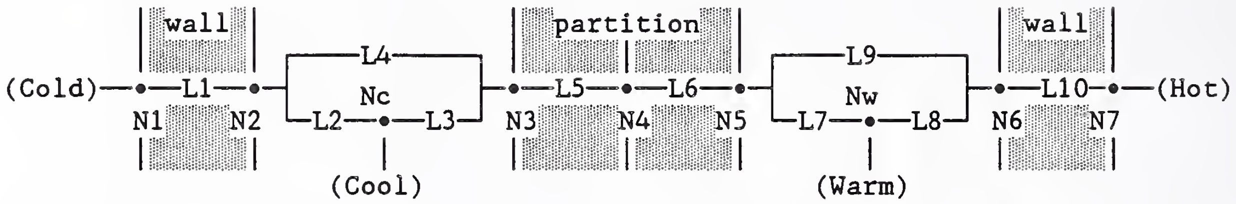


```
signal LowerLimit t 70.
signal UpperLimit t 75.

node node-a1 air c 1. 70. 75. 70. 100.  LowerLimit UpperLimit
node node-s1 srf v 1. 69. 76. 70. 100. .90
node node-o1 srf v 1. 60. 85. 60. 100. .90
node node-a2 air c 1. 70. 75. 70. 0.0   LowerLimit UpperLimit   massless air
node node-s2 srf v 1. 69. 76. 70. 100. .90
node node-o2 srf v 1. 60. 85. 60. 100. .90
node ambient air b 1. 60. 85. 60. 100.

element InsWall mat 0.0 0.0 0.0 0.0 8.0

link link-a1 hcc  1.0    node-s1 node-a1
link link-s1 cnd InsWall node-o1 node-s1
link link-o1 hcc  1.0    node-o1 ambient

link link-a2 hcc  1.0    node-s2 node-a2
link link-s2 cnd InsWall node-o2 node-s2
link link-o2 hcc  1.0    node-o2 ambient

times 1 300

report test3b.rpt  7  300
node  ambient  T  i  %8.3f
node  node-s1  T  i  %8.3f
node  node-a1  T  i  %8.3f
node  node-a1  Q  i  %9.3f
node  node-s2  T  i  %8.3f
node  node-a2  T  i  %8.3f
node  node-a2  Q  i  %9.3f

display  3  300
node  ambient  T  i  %8.3f
node  node-a1  T  i  %8.3f
node  node-a2  T  i  %8.3f

* end of data
```

The BVF is set up to cause the temperature to increase from 60°F to 85°F during the first two hours of simulation and return to 60°F during the last two hours.

```
001/00:00:00    50.000  60.000  70.000    0.000  60.000  70.000    0.000
001/00:05:00    61.042  69.104  70.000   89.583  69.104  70.000   89.583
001/00:10:00    62.083  69.208  70.000   79.167  69.208  70.000   79.167
001/00:15:00    63.125  69.312  70.000   68.750  69.312  70.000   68.750
001/00:20:00    64.167  69.417  70.000   58.333  69.417  70.000   58.333
001/00:25:00    65.208  69.521  70.000   47.917  69.521  70.000   47.917
001/00:30:00    66.250  69.625  70.000   37.500  69.625  70.000   37.500
001/00:35:00    67.292  69.729  70.000   27.083  69.729  70.000   27.083
001/00:40:00    68.333  69.833  70.000   16.667  69.833  70.000   16.667
001/00:45:00    69.375  69.937  70.000    6.250  69.937  70.000    6.250
001/00:50:00    70.417  70.042  70.192    0.000  70.042  70.018    0.000
001/00:55:00    71.458  70.679  70.592    0.000  71.458  71.458    0.000
001/01:00:00    72.500  71.326  71.195    0.000  72.500  72.500    0.000
001/01:05:00    73.542  72.097  71.936    0.000  73.542  73.542    0.000
001/01:10:00    74.583  72.954  72.773    0.000  74.583  74.583    0.000
001/01:15:00    75.625  73.869  73.674    0.000  75.625  75.000   -0.000
001/01:20:00    76.667  74.824  74.619    0.000  75.167  75.000  -16.666
001/01:25:00    77.708  75.807  75.000  -12.890  75.271  75.000  -27.083
001/01:30:00    78.750  75.375  75.000  -37.500  75.375  75.000  -37.500
001/01:35:00    79.792  75.479  75.000  -47.916  75.479  75.000  -47.916
001/01:40:00    80.833  75.583  75.000  -58.333  75.583  75.000  -58.333
001/01:45:00    81.875  75.687  75.000  -68.750  75.687  75.000  -68.750
001/01:50:00    82.917  75.792  75.000  -79.166  75.792  75.000  -79.166
001/01:55:00    83.958  75.896  75.000  -89.583  75.896  75.000  -89.583
001/02:00:00    85.000  76.000  75.000  -100.00  76.000  75.000  -100.00
001/02:05:00    83.958  75.896  75.000  -89.583  75.896  75.000  -89.583
001/02:10:00    82.917  75.792  75.000  -79.167  75.792  75.000  -79.167
001/02:15:00    81.875  75.688  75.000  -68.750  75.688  75.000  -68.750
001/02:20:00    80.833  75.583  75.000  -58.333  75.583  75.000  -58.333
001/02:25:00    79.792  75.479  75.000  -47.917  75.479  75.000  -47.917
001/02:30:00    78.750  75.375  75.000  -37.500  75.375  75.000  -37.500
001/02:35:00    77.708  75.271  75.000  -27.083  75.271  75.000  -27.083
001/02:40:00    76.667  75.167  75.000  -16.667  75.167  75.000  -16.667
001/02:45:00    75.625  75.063  75.000   -6.250  75.063  75.000   -6.250
001/02:50:00    74.583  74.958  74.808    0.000  74.958  74.982    0.000
001/02:55:00    73.542  74.321  74.408    0.000  73.542  73.542    0.000
001/03:00:00    72.500  73.674  73.805    0.000  72.500  72.500    0.000
001/03:05:00    71.458  72.903  73.064    0.000  71.458  71.458    0.000
001/03:10:00    70.417  72.046  72.227    0.000  70.417  70.417    0.000
001/03:15:00    69.375  71.131  71.326    0.000  69.375  70.000    0.000
001/03:20:00    68.333  70.176  70.381    0.000  69.833  70.000   16.666
001/03:25:00    67.292  69.193  70.000   12.890  69.729  70.000   27.083
001/03:30:00    66.250  69.625  70.000   37.500  69.625  70.000   37.500
001/03:35:00    65.208  69.521  70.000   47.916  69.521  70.000   47.916
001/03:40:00    64.167  69.417  70.000   58.333  69.417  70.000   58.333
001/03:45:00    63.125  69.313  70.000   68.750  69.313  70.000   68.750
001/03:50:00    62.083  69.208  70.000   79.166  69.208  70.000   79.166
001/03:55:00    61.042  69.104  70.000   89.583  69.104  70.000   89.583
001/04:00:00    60.000  69.000  70.000   100.00  69.000  70.000   100.00
```

TEST4A checks the calculation of radiant heat transfer.



This test uses a mode complex thermal network representing two walls bounding two air spaces which are separated by an almost infinite resistance partition. The outside surface temperatures and the air temperatures are set constant. If there is no heat conduction through the partition, the temperatures of the four nodes bounding the two air spaces can be computed by solving two pairs of simultaneous non-linear equations.

The corresponding NDF description is:

```
signal ColdSurface t 48.
signal HotSurface  t 98.
signal CoolRoom    t 68.
signal WarmRoom    t 78

node node-1 lyr c 1. 48. 48. 48. 2000.  ColdSurface
node node-2 srf v 1. 48. 68. 60. 2000.  .90
node node-c air c 1. 68. 68. 68. 10000. CoolRoom  CoolRoom
node node-3 srf v 1. 68. 68. 68. 2000.  .90
node node-4 lyr v 1. 68. 78. 73. 2000.
node node-5 srf v 1. 78. 78. 78. 2000.  .90
node node-w air c 1. 78. 78. 78. 10000. WarmRoom  WarmRoom
node node-6 srf v 1. 78. 98. 80. 2000.  .90
node node-7 lyr c 1. 98. 98. 98. 2000.  HotSurface

element ExtWall   mat  0.0 0.0 0.0 0.0 4.0
element Partition mat  0.0 0.0 0.0 0.0 1.0e8

link link-1 cnd ExtWall   node-1 node-2
link link-2 hcc 0.5424    node-2 node-c
link link-3 hcc 0.5424    node-3 node-c
link link-4 rad 0.818182  node-2 node-3
link link-5 cnd Partition node-3 node-4
link link-6 cnd Partition node-4 node-5
link link-7 rad 0.818182  node-5 node-6
link link-8 hcc 0.5424    node-5 node-w
link link-9 hcc 0.5424    node-6 node-w
link link-10 cnd ExtWall  node-6 node-7
```

(continued on next page)

```
times 1 900

report test4a.rpt  6  900
node  node-2  T  i  %8.4f
node  node-3  T  i  %8.4f
node  node-5  T  i  %8.4f
node  node-6  T  i  %8.4f
node  node-c  Q  a  %12.5e
node  node-w  Q  a  %12.5e

display  6  900
node  node-2  T  i  %8.4f
node  node-c  T  i  %8.4f
node  node-3  T  i  %8.4f
node  node-5  T  i  %8.4f
node  node-w  T  i  %8.4f
node  node-6  T  i  %8.4f

* end of data
```

For the "cool" side of the network, there are four active heat transfer paths:

(1) link-1 $q_1 = U (T_1 - T_2)$ conduction in the exterior wall,
(2) link-2 $q_2 = H (T_2 - T_c)$ convection from the wall to the air,
(3) link-3 $q_3 = H (T_3 - T_c)$ convection from the partition to the air, and
(4) link-4 $q_4 = \sigma F (T_2^4 - T_3^4)$ radiation from the wall to the partition.

$U = 0.25$ Btu/h·ft^2·°F; $H = 0.5424$ Btu/h·ft^2·°F;
$\sigma = 1.7141E-9$ Btu/h·ft^2·R^4 (Stefan-Boltzmann constant);
$F = 1 / (1/\epsilon_1 + 1/\epsilon_2 - 1) = 0.818182$ for $\epsilon_1 = \epsilon_2 = 0.90$ (radiation interchange factor between two surfaces which can see only each other).

This leads to the following heat balances at surfaces 2 and 3:
$q_1 - q_2 - q_4 = 0$, and $q_4 - q_3 = 0$, respectively.

Solving these equations simultaneously with $T_1 = 48$°F and $T_c = 68$°F gives $T_2 =$ 63.523°F, $T_3 = 65.322$°F, and $q_1 = -3.881$ Btu/h·ft^2. For the entire 2000 ft^2 wall the expected heating load is 7762. Btu/h.

Similarly, for the "warm" side of the network setting $T_7 = 98$°F and $T_w = 78$°F gives $T_6 = 80.752$°F, $T_5 = 82.428$°F, and $q_1{}^0 = 3.893$ Btu/h·ft^2. For the entire 2000 ft^2 wall the expected cooling load is 7786. Btu/h. Note that this load is not exactly equal to the heating load for the cool room even though there is a 20°F temperature difference for both walls. This is caused by the nonlinear nature of radiant heat transfer.

The computed results from file test4a.rpt are:

```
001/00:00:00  60.0000 68.0000 78.0000 80.0000  0.0000e+00  0.0000e+00
001/00:15:00  63.5213 65.3246 80.7389 82.4352  3.8803e+03 -3.8912e+03
001/00:30:00  63.5226 65.3228 80.7495 82.4279  7.7610e+03 -7.7842e+03
001/00:45:00  63.5226 65.3228 80.7495 82.4279  7.7613e+03 -7.7860e+03
001/01:00:00  63.5226 65.3228 80.7495 82.4279  7.7613e+03 -7.7860e+03
     time        T2      T3      T6      T5        Qw          Qc
```

TEST4B is identical to test4a except that view factor, vfm, links are used in place of the radiant interchange, rad, links. The link portion of the test4b NDF is:

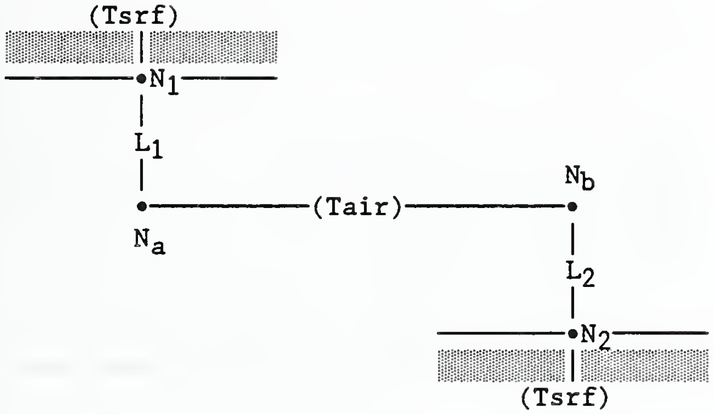
```
link link-1 cnd ExtWall   node-1 node-2
link link-2 hcc 0.5424    node-2 node-c
link link-3 hcc 0.5424    node-3 node-c
link link-4 vfm 2
  node-2
    0.0  1.0
  node-3
    1.0  0.0
link link-5 cnd Partition node-3 node-4
link link-6 cnd Partition node-4 node-5
link link-7 vfm 2
  node-5
    0.0  1.0
  node-6
    1.0  0.0
link link-8 hcc 0.5424    node-5 node-w
link link-9 hcc 0.5424    node-6 node-w
link link-10 cnd ExtWall  node-6 node-7
```

Note that node-2 has a view factor of 0.0 to itself and 1.0 to node-3; node-3 has a view factor of 1.0 to node-2 and 0.0 to itself. This is physically identical to the situation simulated in test4a. Therefore, the results of simulation should be identical, which is confirmed by the output file test2b.rpt:

```
001/00:00:00  60.0000 68.0000 78.0000 80.0000  0.0000e+00  0.0000e+00
001/00:15:00  63.5213 65.3246 80.7389 82.4352  3.8803e+03 -3.8912e+03
001/00:30:00  63.5226 65.3228 80.7495 82.4279  7.7610e+03 -7.7842e+03
001/00:45:00  63.5226 65.3228 80.7495 82.4279  7.7613e+03 -7.7860e+03
001/01:00:00  63.5226 65.3228 80.7495 82.4279  7.7613e+03 -7.7860e+03
```

This output shows how nonlinearities are handled over several timesteps.

TEST5A checks the simple models for the variable convection coefficient element.



```
signal Tair     t 70.
signal Tsrf     t 50.
signal flow     d 0.0

node node-a air c 1. 70. 70. 70. 100.  Tair Tair
node node-b air c 1. 70. 70. 70. 100.  Tair Tair
node node-1 srf c 1. 50. 90. 50. 10.  .90   Tsrf
node node-2 srf c 1. 50. 90. 50. 10.  .90   Tsrf

element hs_ceil  hcv 1.08 0.0
0.162 0.0 0.0 0.712 0.0 0.0
element hs_wall  hcv 1.08 0.0
0.542 0.0 0.0 0.542 0.0 0.0
element hs_floor hcv 1.08 0.0
0.712 0.0 0.0 0.162 0.0 0.0
element flow cfr 1.0

link link-0 afp flow node-a node-b flow
link link-1 cnv hs_ceil  node-1 node-a link-0
link link-2 cnv hs_floor node-2 node-b link-0

times 1 300

report test5a.rpt  7  300
node   node-a  T  i  %8.4f
node   node-1  T  i  %8.4f
node   node-2  T  i  %8.4f
node   node-a  Q  i  %12.5e
node   node-b  Q  i  %12.5e
link   link-1  h  i  %8.4f
link   link-2  h  i  %8.4f

display  3  300
node   node-a  T  i  %8.4f
node   node-a  Q  i  %12.5e
node   node-b  Q  i  %12.5e

* end of data
```

← Since the ϵ coefficient is 0, the VA_e and flow values in the <u>cnv</u> links below are not needed.

Begining at Tair = 70°F and Tsrf = 50°F, Tsrf is incremented by 5°F up to 90°F. The following DEF file was used:

```
00:00:00
00:10:00  Tsrf  55.
00:20:00  Tsrf  60.
00:30:00  Tsrf  65.
00:40:00  Tsrf  70.
00:50:00  Tsrf  75.
01:00:00  Tsrf  80.
01:10:00  Tsrf  85.
01:20:00  Tsrf  90.
01:30:00  flow  1.0
```

The expected loads, given by $Q = h \cdot A \cdot (Tsrf - Tair)$, are:

Tsrf	Q_1	Q_2
50.0	142.4	32.4
55.0	106.8	24.3
60.0	71.2	16.2
65.0	35.6	8.1
70.0	0.0	0.0
75.0	-8.1	-35.6
80.0	-16.2	-71.2
85.0	-24.3	-106.8
90.0	-32.4	-142.4

After the flow signal is set, the expected load is

$$Q = -h \cdot A \cdot \Delta T = 1.08 \cdot 10 \cdot (90 - 70) = 216.0 \text{ Btu/h.}$$

Five minute time steps reporting intervals were used. All the temperatures are fixed; none are computed. HLITE produced the following RPT file:

```
001/00:00:00   70.0000 50.0000 50.0000  0.0000e+00  0.0000e+00  0.0000  0.0000
001/00:05:00   70.0000 50.0000 50.0000  1.4240e+02  3.2400e+01  0.7120  0.1620
001/00:10:00   70.0000 55.0000 55.0000  1.4240e+02  3.2400e+01  0.7120  0.1620
001/00:15:00   70.0000 55.0000 55.0000  1.0680e+02  2.4300e+01  0.7120  0.1620
001/00:20:00   70.0000 60.0000 60.0000  1.0680e+02  2.4300e+01  0.7120  0.1620
001/00:25:00   70.0000 60.0000 60.0000  7.1200e+01  1.6200e+01  0.7120  0.1620
001/00:30:00   70.0000 65.0000 65.0000  7.1200e+01  1.6200e+01  0.7120  0.1620
001/00:35:00   70.0000 65.0000 65.0000  3.5600e+01  8.1000e+00  0.7120  0.1620
001/00:40:00   70.0000 70.0000 70.0000  3.5600e+01  8.1000e+00  0.7120  0.1620
001/00:45:00   70.0000 70.0000 70.0000  0.0000e+00  0.0000e+00  0.1620  0.7120
001/00:50:00   70.0000 75.0000 75.0000  0.0000e+00  0.0000e+00  0.1620  0.7120
001/00:55:00   70.0000 75.0000 75.0000 -8.1000e+00 -3.5600e+01  0.1620  0.7120
001/01:00:00   70.0000 80.0000 80.0000 -8.1000e+00 -3.5600e+01  0.1620  0.7120
001/01:05:00   70.0000 80.0000 80.0000 -1.6200e+01 -7.1200e+01  0.1620  0.7120
001/01:10:00   70.0000 85.0000 85.0000 -1.6200e+01 -7.1200e+01  0.1620  0.7120
001/01:15:00   70.0000 85.0000 85.0000 -2.4300e+01 -1.0680e+02  0.1620  0.7120
001/01:20:00   70.0000 90.0000 90.0000 -2.4300e+01 -1.0680e+02  0.1620  0.7120
001/01:25:00   70.0000 90.0000 90.0000 -3.2400e+01 -1.4240e+02  0.1620  0.7120
001/01:30:00   70.0000 90.0000 90.0000 -3.2400e+01 -1.4240e+02  0.1620  0.7120
001/01:35:00   70.0000 90.0000 90.0000 -2.1600e+02 -2.1600e+02  1.0800  1.0800
. . .
001/02:00:00   70.0000 90.0000 90.0000 -2.1600e+02 -2.1600e+02  1.0800  1.0800
                  Tair      T1      T2      Q1          Q2          h1      h2
```

TEST5B is similar to TEST5A except that the detailed convection models are used instead of the simple models.

```
signal Tair     t 70.
signal Tsrf     t 50.
signal flow     d 0.0

node node-a air c 1. 70. 70. 70. 100.  Tair Tair
node node-b air c 1. 70. 70. 70. 100.  Tair Tair
node node-1 srf c 1. 50. 90. 50. 10.  .90   Tsrf
node node-2 srf c 1. 50. 90. 50. 10.  .90   Tsrf

element hd_ceil  hcv 2.01 36.9
0.0 0.10 0.33 0.0 0.22 0.33
element hd_wall  hcv 0.74 14.3
0.0 0.19 0.33 0.0 0.19 0.33
element hd_floor hcv 0.62 8.24
0.0 0.22 0.33 0.0 0.10 0.33
element flow cfr 100.

link link-0 afp flow node-a node-b flow
link link-1 cnv hd_ceil  node-1 node-1 link-0 1000. 100.
link link-2 cnv hd_floor node-2 node-b link-0 1000. 100.
```

The VA_e value of 1000 in the cnv link represents a room volume of 1000 ft^3 (matching the volumes of node-a and node-b) and a flow area of 1 ft^2. The flow rate of 100 cfm gives a maximum air velocity of 100 ft/s and 6 air changes per hour. This flow rate in the links matches the flow rate in the element.

Begining at Tair = 70°F and Tsrf = 50°F, Tsrf is incremented by 5°F up to 90°F. The expected loads at the air nodes, given by

$Q = -h \cdot A \cdot \Delta T = -h' \cdot A \cdot (Tsrf - Tair)^{1.33}$ where $h' = 0.22$ or 0.10 are:

Tsrf	Q_1	Q_2
50.0	118.2	53.7
55.0	80.7	36.7
60.0	47.0	21.4
65.0	18.7	8.5
70.0	0.0	0.0
75.0	-8.5	-18.7
80.0	-21.4	-47.0
85.0	-36.7	-80.7
90.0	-53.7	-118.2

After the flow signal is set, the square root of the jet momentum number is

$$\sqrt{J} = F \ / \ \rho\sqrt{gVA_e} = (100 \cdot .075/60)/(.075 \cdot \sqrt{32.2 \cdot 1000 \cdot 1}) = 0.009288$$

and the expected loads are

$$Q_c = -h \cdot A \cdot \Delta T = -(2.01 + 36.9 \ \sqrt{J}) \cdot 10 \cdot (90 - 70) = -470.5 \text{ Btu/h and}$$

$$Q_f = -(0.62 + 8.24 \ \sqrt{J}) \cdot 10 \cdot (90 - 70) = -139.3 \text{ Btu/h.}$$

TEST5C is a variation of TEST5A in which the cnv links refer to the null node, which causes the effect of air flow rate to be ignored in computing convection coefficients.

```
signal Tair     t 70.
signal Tsrf     t 50.
signal flow     d 0.0

node node-a air c 1. 70. 70. 70. 100.  Tair Tair
node node-b air c 1. 70. 70. 70. 100.  Tair Tair
node node-1 srf c 1. 50. 90. 50. 10.  .90   Tsrf
node node-2 srf c 1. 50. 90. 50. 10.  .90   Tsrf

element hs_ceil  hcv 1.08 0.0
0.162 0.0 0.0 0.712 0.0 0.0
element hs_wall  hcv 1.08 0.0
0.542 0.0 0.0 0.542 0.0 0.0
element hs_floor hcv 1.08 0.0
0.712 0.0 0.0 0.162 0.0 0.0
element flow cfr 1.0

link link-0 afp flow node-a node-b flow
link link-1 cnv hs_ceil  node-1 node-a null    <---- null link used
link link-2 cnv hs_floor node-2 node-b null

. . .
```

TEST6A checks the operation of the luminaire performance curves. By varying the air temperature, the luminaire temperature is changed. All light is absorbed by the "Walls" surface so that the cooling load for that surface equals the light emitted from the luminaire. Similarly, the load at the "Ballast" surface equals the power into the ballast.

```
signal air-temp t 50.
signal switch d 1.0

node RoomAir air c 1. 50. 130. 50. 100.  air-temp air-temp
node Housing mas v 1. 50. 140. 50. 10.  0.1  0.2  .90
node Adb1    lyr c 1. 50. 130. 50. 10.  air-temp
node Walls   srf v 1. 50. 140. 50. 10.  .90
node Adb2    lyr c 1. 50. 130. 50. 10.  air-temp
node Luminaire eqp v 1. 50. 141. 50.

element tube  lmp  48.0  3200.  372.  1.57  0.90  0.64  .2  11
      0.0         0.661        0.022
     20.0         0.672        0.068    (Ref: IES Lighting Handbook,
     40.0         0.704        0.165     Ref Volume, 1984, Fig 8-34)
     60.0         0.818        0.476
     70.0         0.894        0.701
     80.0         0.971        0.865
     90.0         0.999        0.960
    100.0         0.965        0.995
    120.0         0.858        0.850
    140.0         0.721        0.697
    215.0         0.000        0.000

link light   lum tube  2  Luminaire  5.
    switch .15 Ballast 1
    Walls   1.0
link ballast knd  5.0     Ballast Adb1
link walls   knd  5.0     Walls   Adb2
link tubes   hcc  5.0     Luminaire RoomAir

times 1 120

report  test6a.rpt  6  360
node  RoomAir    T  i  %8.3f
node  Luminaire  T  i  %8.3f
link  light      Q  i  %9.3f
node  RoomAir    Q  i  %9.3f
node  Adb1       Q  i  %9.3f
node  Adb2       Q  i  %9.3f

display  3  360
node  RoomAir    Q  i  %9.3f
node  Luminaire  T  i  %8.3f
node  Ballast    T  i  %8.3f

* end of data
```

Contents of the DEF:

```
001/00:00:00
001/01:00:00  air-temp  55.
001/02:00:00  air-temp  60.
001/03:00:00  air-temp  65.
001/04:00:00  air-temp  70.
001/05:00:00  air-temp  75.
001/06:00:00  air-temp  80.
001/07:00:00  air-temp  85.
001/08:00:00  air-temp  90.
001/09:00:00  air-temp  95.
001/10:00:00  air-temp 100.
001/11:00:00  air-temp 105.
001/12:00:00  air-temp 110.
001/13:00:00  air-temp 115.
001/14:00:00  air-temp 120.
001/15:00:00  air-temp 125.
001/16:00:00  air-temp 130.
002/00:00:00
*
```

The following results were selected from the report file after disappearance of the transients due to temperature change.

```
001/00:00:00    50.000  50.000    0.000    0.000    0.000    0.000
001/00:30:00    50.000  62.618   76.919 -198.103  -39.369  -24.987
001/01:30:00    55.000  67.852   80.510 -201.782  -41.207  -31.724
001/02:30:00    60.000  73.114   84.365 -205.894  -43.180  -38.792
001/03:30:00    65.000  78.499   88.609 -211.934  -45.352  -45.059
001/04:30:00    70.000  83.917   92.560 -218.498  -47.374  -49.955
001/05:30:00    75.000  89.163   95.117 -222.355  -48.683  -53.515
001/06:30:00    80.000  94.156   95.938 -222.244  -49.103  -56.007
001/07:30:00    85.000  98.899   95.127 -218.221  -48.688  -57.678
001/08:30:00    90.000 103.518   93.318 -212.233  -47.762  -58.418
001/09:30:00    95.000 108.150   91.163 -206.451  -46.659  -57.952
001/10:30:00   100.000 112.830   88.888 -201.436  -45.495  -56.367
001/11:30:00   105.000 117.534   86.484 -196.778  -44.264  -54.052
001/12:30:00   110.000 122.231   83.941 -192.030  -42.963  -51.427
001/13:30:00   115.000 126.896   81.256 -186.760  -41.589  -48.909
001/14:30:00   120.000 131.514   78.427 -180.776  -40.140  -46.687
001/15:30:00   125.000 136.094   75.456 -174.177  -38.620  -44.670
001/16:30:00   130.000 140.641   72.346 -167.070  -37.028  -42.756
                   air    lamp     lamp      air  ballast    walls
                    °F      °F        W    Btu/h    Btu/h    Btu/h
```

Note: 1 W = 3.4123 Btu/h; 1 Btu/h = 0.2931 W

The sum of the cooling loads should be equal to (minus) the power into the light.

TEST6B checks the transient operation of the luminaire model, in particular the effect of using different time steps. The thermal network consists of the lamps linked radiatively to wall and housing surfaces and room air linked convectively to all surfaces. Nonlinear convection and radiation models are used. DIfferent simulation time steps are used. The summary reports indicate the lighting energy and cooling requirements for each hour. The lights are turned on at 01:00:00.

```
signal air-temp t 50.
signal switch d 0.0

node Housing mas v 1. 50. 80. 50. 6.283  10.  0.2  .90     6" dia, 10# mass
node Lum_Air air v 1. 50. 100. 50. 0.785                    6" dia, 4' long
node Tubes   eqp v 1. 50. 120. 50.
node RoomAir air c 1. 50. 50. 50. 100.  air-temp air-temp
node Walls   mas v 1. 50. 51. 50. 400. 10.  0.2  .90

element hd_tube  hcv 0.0  0.0
0.0 0.19 0.33 0.0 0.19 0.33
element tube  lmp  48.0  3200.  372.  1.57  0.90  0.64  .2  11
      0.0         0.661        0.022
     20.0         0.672        0.068    (Ref: IES Lighting Handbook,
     40.0         0.704        0.165     Ref Volume, 1984, Fig 8-34)
     60.0         0.818        0.476
     70.0         0.894        0.701
     80.0         0.971        0.865
     90.0         0.999        0.960
    100.0         0.965        0.995
    120.0         0.858        0.850
    140.0         0.721        0.697
    215.0         0.000        0.000

link light  lum tube  2  Tubes    5.
    switch .15 Housing 2
    Housing 0.1
    Walls   0.9
link link-1 cnv  hd_tube  Housing   Lum_Air  null
link link-2 cnv  hd_tube  Tubes     Lum_Air  null
link link-3 hcc   1.50    Housing   RoomAir
link link-4 rad  0.8572   Tubes     Housing   A1=3.14; A2=6.283
/ sF = 1 / ( (1-.9)/.9 + 1 + 3.14*(1-.9)/(6.28*.9) )
link link-5 hcc   1.00    Walls   RoomAir
/ link Link-6 knd   4.0     Housing  Tubes

times 1 240
```

(continued)

```
report  test6b.rpt  5  300
link  light      Q  i  %9.3f
node  RoomAir    Q  i  %9.3f
node  Luminaire  T  i  %8.3f
node  Housing    T  i  %8.3f
node  Walls      T  i  %8.3f

report  test6b.sum  2  3600
link  light      Q  s  %9.3f
node  RoomAir    Q  s  %9.3f

display  3  300
node  RoomAir    Q  i  %12.4f
node  Luminaire  T  i  %8.3f
node  Housing    T  i  %8.3f

* end of data
```

Results:

```
10 second time step
001/00:59:00     0.000   -0.000  50.000  50.000  50.000
001/01:00:00    69.609   -0.000  50.000  50.000  50.000
001/01:01:00    75.159  -73.223  61.722  59.749  50.072
001/01:02:00    81.868 -133.862  71.162  63.400  50.138
001/01:03:00    87.702 -186.824  78.447  66.407  50.194
001/01:04:00    92.122 -228.160  84.082  68.768  50.234
001/01:05:00    94.581 -259.286  88.360  70.513  50.263
001/01:06:00    95.619 -281.776  91.457  71.725  50.283
001/01:07:00    95.920 -297.329  93.597  72.532  50.297
001/01:08:00    95.915 -307.702  95.022  73.055  50.306
001/01:09:00    95.821 -314.434  95.945  73.387  50.312
001/01:10:00    95.725 -318.722  96.532  73.595  50.316
001/01:11:00    95.651 -321.422  96.902  73.725  50.318
001/01:12:00    95.599 -323.110  97.133  73.806  50.320
001/01:13:00    95.565 -324.162  97.277  73.856  50.320
001/01:14:00    95.544 -324.815  97.367  73.887  50.321
001/01:15:00    95.530 -325.221  97.423  73.906  50.321
001/01:16:00    95.521 -325.473  97.457  73.918  50.322
001/01:17:00    95.516 -325.628  97.478  73.926  50.322
001/01:18:00    95.512 -325.725  97.492  73.930  50.322
001/01:19:00    95.510 -325.785  97.500  73.933  50.322
001/01:20:00    95.509 -325.822  97.505  73.935  50.322
 ...
001/02:00:00    95.507 -325.882  97.513  73.938  50.322

001/01:00:00     0.097    0.000     summary
001/02:00:00    94.554 -308.770
001/03:00:00    95.506 -325.881
```

```
60 second time step
001/00:59:00      0.000     0.000  50.000  50.000  50.000
001/01:00:00     69.609   -31.166  50.000  55.573  50.022
001/01:01:00     69.609   -62.345  62.834  59.353  50.062
001/01:02:00     77.063  -131.548  72.410  62.982  50.121
001/01:03:00     83.832  -185.860  79.715  66.104  50.180
001/01:04:00     89.561  -228.850  85.117  68.586  50.226
001/01:05:00     93.283  -260.905  89.228  70.447  50.258
001/01:06:00     95.139  -284.379  92.298  71.778  50.281
001/01:07:00     95.832  -300.793  94.429  72.673  50.297
001/01:08:00     95.933  -311.533  95.795  73.234  50.308
001/01:09:00     95.824  -318.079  96.604  73.564  50.314
001/01:10:00     95.698  -321.809  97.050  73.746  50.318
001/01:11:00     95.610  -323.818  97.282  73.841  50.320
001/01:12:00     95.560  -324.856  97.400  73.890  50.321
001/01:13:00     95.533  -325.378  97.458  73.914  50.321
001/01:14:00     95.520  -325.637  97.486  73.926  50.322
001/01:15:00     95.513  -325.763  97.500  73.932  50.322
001/01:16:00     95.510  -325.825  97.507  73.935  50.322
001/01:17:00     95.508  -325.854  97.510  73.936  50.322
001/01:18:00     95.507  -325.869  97.512  73.937  50.322
001/01:19:00     95.507  -325.876  97.512  73.937  50.322
001/01:20:00     95.507  -325.879  97.513  73.938  50.322
 ...
001/02:00:00     95.507  -325.882  97.513  73.938  50.322

001/01:00:00      0.580    -0.260     summary
001/02:00:00     94.240  -309.147
001/03:00:00     95.507  -325.882


300 second time step
001/00:55:00      0.000     0.000  50.000  50.000  50.000
001/01:00:00     69.609  -120.616  85.698  65.490  50.147
001/01:05:00     93.605  -287.547  94.491  72.098  50.282
001/01:10:00     95.931  -318.365  97.039  73.652  50.314
001/01:15:00     95.613  -324.756  97.451  73.900  50.321
001/01:20:00     95.521  -325.732  97.505  73.933  50.322
001/01:25:00     95.509  -325.863  97.512  73.937  50.322
001/01:30:00     95.507  -325.880  97.513  73.938  50.322
001/01:35:00     95.507  -325.882  97.513  73.938  50.322
001/01:40:00     95.507  -325.882  97.513  73.938  50.322

001/01:00:00      2.900    -5.026     summary
001/02:00:00     94.315  -313.400
001/03:00:00     95.507  -325.882
```

These results indicate that the choice of time step has very little difference on the modeling of luminaire performance. This test should probably be performed on each piece of equipment to insure that an appropriate time step is being used.

TEST6C is a test of the generic equipment model and the DEF signal controls. The computed loads relate directly to the equipment capacities.

```
signal air-temp t 70.
signal switch d 1.0

node RoomAir1 air c 1. 70. 70. 70. 1000.  air-temp air-temp
node Equip1   eqp v 1. 70. 77. 70.
node RoomAir2 air c 1. 70. 70. 70. 1000.  air-temp air-temp
node Equip2   eqp v 1. 70. 77. 70.

element WithMass   eqp  100.  5.0  0.90  20.0  0.2
element Massless   eqp  100.  5.0  0.90  20.0  0.0

link eqp1    eqp WithMass  2  Equip1  switch
link fan1    hcc 10.0  Equip1  RoomAir1
link eqp2    eqp Massless  1  Equip2  switch
link fan2    hcc 10.0  Equip2  RoomAir2

times 1 120

report  test6c.rpt  4  120
node  Equip1     T  i  %8.3f
node  RoomAir1   Q  i  %9.3f
node  Equip2     T  i  %8.3f
node  RoomAir2   Q  i  %9.3f

display  4  120
node  Equip1     T  i  %8.3f
node  RoomAir1   Q  i  %9.3f
node  Equip2     T  i  %8.3f
node  RoomAir2   Q  i  %9.3f

* end of data
```

Contents of DEF:

```
001/00:00:00
001/00:30:00  switch   1.0
001/01:00:00  switch   0.5
001/01:30:00  switch   1.0
001/02:30:00  switch   0.0
002/00:00:00
```

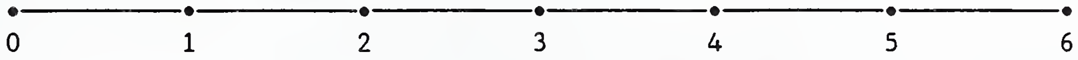
TEST6D is a test of the modeling of nonlinear effects in a case involving very fast transients. Testing at different time steps indicates the largest time step necessary to get an accurate solution. This model of a 100 watt light bulb indicates the smallest time step necessary to model thermal equipment.

```
signal air-temp t 77.
signal switch d 0.0

node RoomAir  air c 1. 75. 79. 77. 10.  air-temp air-temp
node Bulb     eqp v 1. 75. 380. 77.
node Surface  mas v 1. 75. 79. 77. 1000.  0.01  0.20  0.9

element 100Wbulb   eqp  100.  0.213  0.90  0.06  0.2
element hcsphere   hcv  0  0
0.118 0.785 0.25  0.118 0.786 0.25

link eqp1    eqp 100Wbulb  1  Bulb  switch
link convec  cnv hcsphere  Bulb  RoomAir  null
link radnt   rad  0.8981  Bulb  Surface
link hcs     hcc 1.0  Surface RoomAir

times 1 60

report  test6d.rpt  3  60
node  Bulb     T  i  %8.3f
node  RoomAir  Q  i  %9.3f
node  Surface  T  i  %8.3f

report  test6d.sum  1  60
node  RoomAir  Q  s  %9.3f

display  2  60
node  Bulb     T  i  %8.3f
node  RoomAir  Q  i  %9.3f

* end of data
```

TEST7A checks the simple air flow calculation procedure. This case consists of a specified air flow from a cold to a warm room creating an easily computed heating load. The interaction of DEF with the control signals is checked.

```
signal Cold t 50.
signal Room t 68.
signal Flow d 1.0

node node-1 air c 1. 32. 50. 50. 1000.  Cold  Cold
node node-2 air c 1. 68. 70. 68. 1000.  Room  Room

element 100cfm cfr 100.

link link-1 afp 100cfm  node-1 node-2 Flow

times 1 3600

report test7a.rpt  3  3600
link  link-1  F  i  %12.5e
node  node-1  Q  i  %12.5e
node  node-2  Q  i  %12.5e

display  2  3600
node  node-1  Q  i  %12.5e
node  node-2  Q  i  %12.5e

* end of data

BVF:
0
001/00:00:00
001/06:00:00

DEF:
001/00:00:00
001/02:00:00 Flow 0.5
001/03:00:00 Cold 32.0
001/04:00:00 Flow 1.0
001/04:00:00 Cold 50.0
001/05:00:00 Room 70.0
002/00:00:00

Results:
001/00:00:00   1.0000e+02  0.0000e+00  0.0000e+00
001/01:00:00   1.0000e+02  0.0000e+00  1.9443e+03
001/02:00:00   5.0000e+01  0.0000e+00  9.7216e+02
001/03:00:00   5.0000e+01 -3.2476e+02  9.7216e+02
001/04:00:00   1.0000e+02  3.2476e+02  3.8886e+03
001/05:00:00   1.0000e+02  0.0000e+00  1.9804e+03
001/06:00:00   1.0000e+02  0.0000e+00  2.1604e+03
```

TEST7B shows what can happen if the simple air flow calculation is used to simulate transient flow in a duct. It consists of seven air nodes connected in series by six airflow paths. Each node contains 100 ft^3 of air, and the air flow rate is 100 ft^3/min. The air node is assumed to represent a fully mixed volume of air.



```
signal Tset t 0.0
signal Flow d 1.0

node node-0 air c 1. 0.0 1.0 0.0 100.  Tset  Tset
node node-1 air v 1. 0.0 1.0 0.0 100.
node node-2 air v 1. 0.0 1.0 0.0 100.
node node-3 air v 1. 0.0 1.0 0.0 100.
node node-4 air v 1. 0.0 1.0 0.0 100.
node node-5 air v 1. 0.0 1.0 0.0 100.
node node-6 air v 1. 0.0 1.0 0.0 100.

element flow cfr 100.

link link-01 afp  flow   node-0 node-1 Flow
link link-12 afp  flow   node-1 node-2 Flow
link link-23 afp  flow   node-2 node-3 Flow
link link-34 afp  flow   node-3 node-4 Flow
link link-45 afp  flow   node-4 node-5 Flow
link link-56 afp  flow   node-5 node-6 Flow

 ...
```

Consider the case of "plug flow" in a duct, i.e., there is no mixing in the direction of flow. In this case a temperature pulse entering at the upstream end of the duct will propagate along the duct without changing shape. This condition is achieved in the model presented above when the time step exactly matches the time for one air change in each air node, or one minute. The results for such a case are:

```
001/00:00:00  0.000 0.000 0.000 0.000 0.000 0.000 0.000
001/00:01:00  0.000 0.000 0.000 0.000 0.000 0.000 0.000
001/00:02:00  1.000 0.000 0.000 0.000 0.000 0.000 0.000
001/00:03:00  1.000 0.998 0.000 0.000 0.000 0.000 0.000
001/00:04:00  1.000 1.000 0.996 0.000 0.000 0.000 0.000
001/00:05:00  1.000 1.000 1.000 0.993 0.000 0.000 0.000
001/00:06:00  1.000 1.000 1.000 1.000 0.991 0.000 0.000
001/00:07:00  1.000 1.000 1.000 1.000 1.000 0.989 0.000
001/00:08:00  1.000 1.000 1.000 1.000 1.000 1.000 0.987
001/00:09:00  1.000 1.000 1.000 1.000 1.000 1.000 1.000
001/00:10:00  1.000 1.000 1.000 1.000 1.000 1.000 1.000
 ...
001/00:15:00  1.000 1.000 1.000 1.000 1.000 1.000 1.000
```

However, when the time step is reduced to 30 seconds or increased to two minutes, the step change in temperature is diffused as it propagates through the duct. This is an inherent property is this solution method and is called "numerical diffusion" as opposed to any real diffusion which might occur.

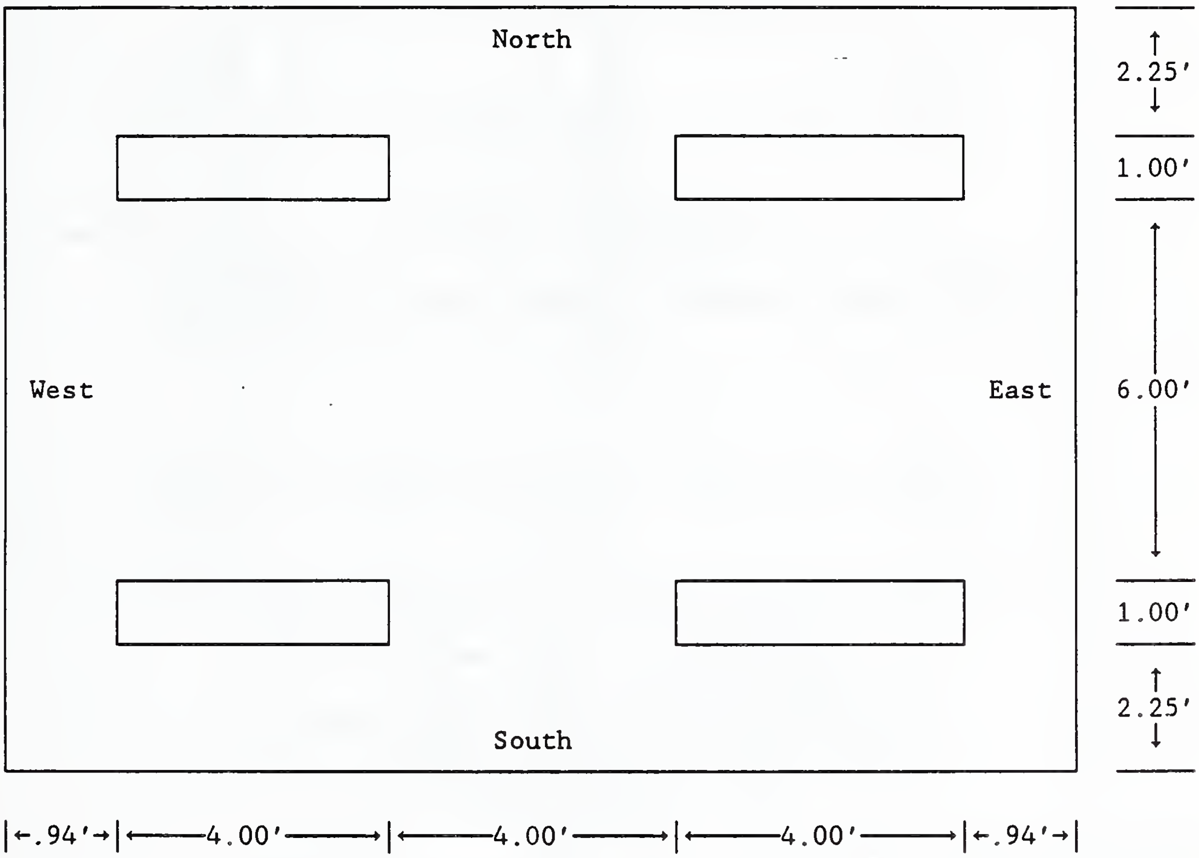
```
time step = 30 seconds:
001/00:00:00  0.000 0.000 0.000 0.000 0.000 0.000 0.000
 ...
001/00:02:00  1.000 0.000 0.000 0.000 0.000 0.000 0.000
001/00:02:30  1.000 0.499 0.000 0.000 0.000 0.000 0.000
001/00:03:00  1.000 0.749 0.249 0.000 0.000 0.000 0.000
001/00:03:30  1.000 0.874 0.498 0.124 0.000 0.000 0.000
001/00:04:00  1.000 0.937 0.686 0.311 0.062 0.000 0.000
001/00:04:30  1.000 0.968 0.811 0.498 0.186 0.031 0.000
001/00:05:00  1.000 0.984 0.890 0.654 0.342 0.108 0.015
001/00:05:30  1.000 0.992 0.937 0.772 0.498 0.225 0.062
001/00:06:00  1.000 0.996 0.964 0.854 0.634 0.361 0.143
001/00:06:30  1.000 0.998 0.980 0.909 0.744 0.497 0.252
001/00:07:00  1.000 0.999 0.989 0.945 0.826 0.620 0.374
001/00:07:30  1.000  1.00 0.994 0.967 0.885 0.723 0.497
001/00:08:00  1.000  1.00 0.997 0.980 0.926 0.804 0.610
001/00:08:30  1.000  1.00 0.998 0.989 0.953 0.865 0.707
001/00:09:00  1.000  1.00 0.999 0.993 0.971 0.909 0.786
001/00:09:30  1.000  1.00 0.999 0.996 0.982 0.940 0.847
001/00:10:00  1.000  1.00  1.00 0.998 0.989 0.961 0.893
001/00:10:30  1.000  1.00  1.00 0.999 0.993 0.975 0.927
001/00:11:00  1.000  1.00  1.00 0.999 0.996 0.984 0.951
001/00:11:30  1.000  1.00  1.00  1.00 0.998 0.990 0.968
001/00:12:00  1.000  1.00  1.00  1.00 0.999 0.994 0.979
001/00:12:30  1.000  1.00  1.00  1.00 0.999 0.996 0.986
001/00:13:00  1.000  1.00  1.00  1.00  1.00 0.998 0.991
001/00:13:30  1.000  1.00  1.00  1.00  1.00 0.999 0.995
001/00:14:00  1.000  1.00  1.00  1.00  1.00 0.999 0.997
001/00:14:30  1.000  1.00  1.00  1.00  1.00  1.00 0.998
001/00:15:00  1.000  1.00  1.00  1.00  1.00  1.00 0.999
```

```
time step = 120 seconds:
001/00:00:00  0.000 0.000 0.000 0.000 0.000 0.000 0.000
001/00:02:00  1.000 0.000 0.000 0.000 0.000 0.000 0.000
001/00:04:00  1.000 0.666 0.444 0.296 0.197 0.131 0.087
001/00:06:00  1.000 0.889 0.740 0.592 0.460 0.350 0.262
001/00:08:00  1.000 0.963 0.888 0.789 0.679 0.570 0.467
001/00:10:00  1.000 0.988 0.954 0.899 0.826 0.740 0.649
001/00:12:00  1.000 0.996 0.982 0.954 0.912 0.854 0.786
001/00:14:00  1.000 0.999 0.993 0.980 0.957 0.923 0.877
```

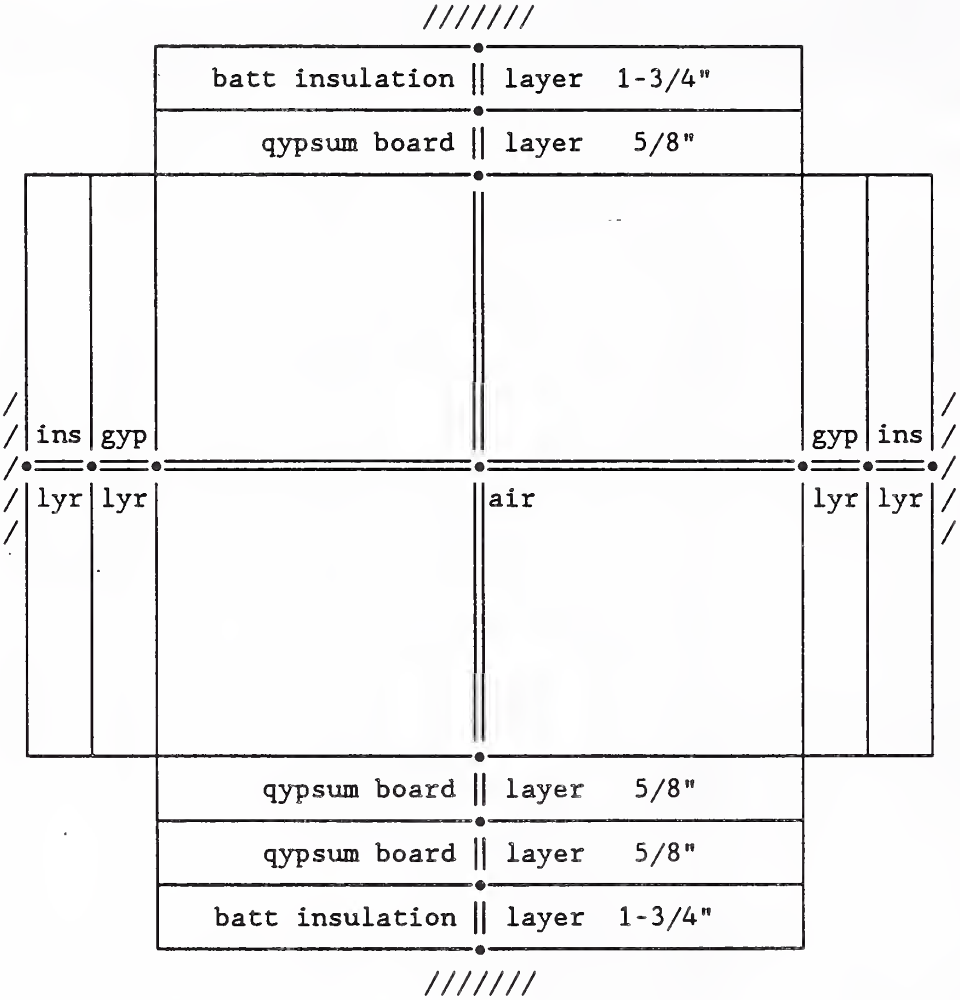
These results indicate that a different solution procedure must be used to model transient flows in ducts. Fortunately, it should be relatively straight forward to develop a method which employs a moving grid system taking advantage of features of the C language.

APPENDIX C: Experimental Test

The NIST Test Room is rectangular room 13'10½" long by 12'3" wide with a suspended ceiling 8' high. Above the ceiling is a 2'6" high plenum. There are four luminaires mounted in the ceiling. The following sketch (not to scale) shows the layout of the luminaires.

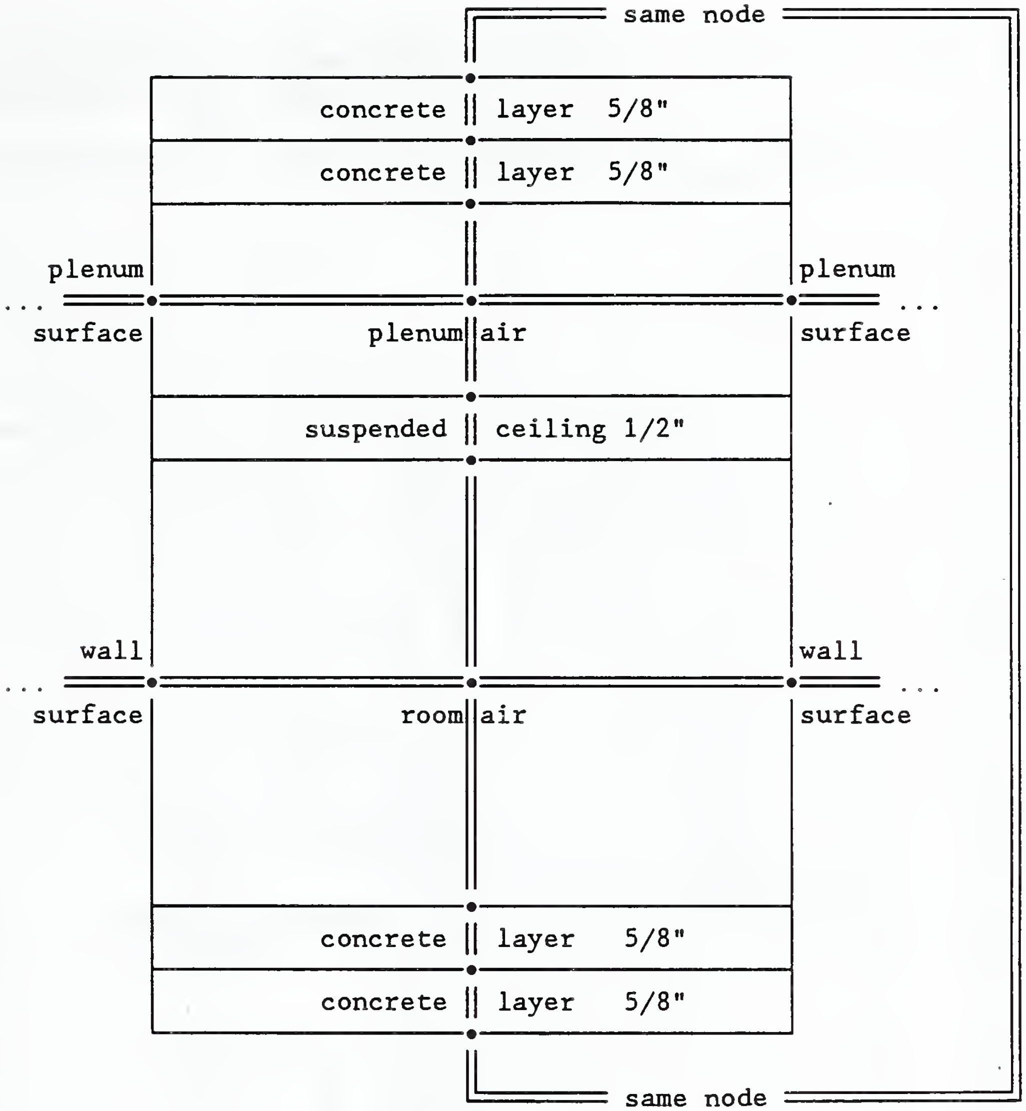


Walls model:

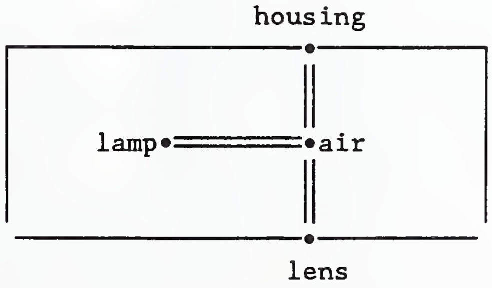


Radiant interchange links between all surfaces are not shown.

Floors and Ceilings:



Luminaire Model:



Data Files:

These features of the NIST test room are described in the following NDF file. This file illustrates that complex simulations require longer data files.

```
/*subfile:  testitb.ndf  ***************************************************/
Simulation of idealized model of NIST test room

signal RoomTemp    t 73.75
signal flow        d 1.0
signal switch      d 0.0

node UnderSide srf v 1. 73.0 77.0 73.75 169.97 0.90
node S-Plenum  srf v 1. 73.0 77.0 73.75  34.69 0.90
node S-Plen-2  lyr v 1. 73.0 77.0 73.75  34.69
node S-Plen-1  lyr v 1. 73.0 77.0 73.75  34.69
node S-Plen-0  lyr v 1. 73.0 77.0 73.75  34.69
node W-Plenum  srf v 1. 73.0 77.0 73.75  30.63 0.90
node W-Plen-1  lyr v 1. 73.0 77.0 73.75  30.63
node W-Plen-0  lyr v 1. 73.0 77.0 73.75  30.63
node N-Plenum  srf v 1. 73.0 77.0 73.75  34.69 0.90
node N-Plen-1  lyr v 1. 73.0 77.0 73.75  34.69
node N-Plen-0  lyr v 1. 73.0 77.0 73.75  34.69
node E-Plenum  srf v 1. 73.0 77.0 73.75  30.63 0.90
node E-Plen-1  lyr v 1. 73.0 77.0 73.75  30.63
node E-Plen-0  lyr v 1. 73.0 77.0 73.75  30.63
node PlenumSC  srf v 1. 73.0 77.0 73.75 153.97 0.90
node Steel     mas v 1. 73.0 77.0 73.75 200.0  625. 0.12 0.90
node PlAir     air v 1. 73.0 77.0 73.75 419.6
node PlLoad    air c 1. 73.0 77.0 73.75 1000.  RoomTemp  RoomTemp
node housing   mas v 1. 73.0 90.0 73.75  29.33  64. 0.21 0.90
node tubes     eqp v .8 73.0 120.0 73.75
node LmAir     air v 1. 73.0 95.0 73.75   5.33
node AcrLens   mas v 1. 73.0 80.0 73.75  16.0   5.4 0.2  0.90
node SspCeil   srf v 1. 73.0 77.0 73.75 153.97 0.90
node S-Wall    srf v 1. 73.0 77.0 73.75 111.00 0.90
node S-Wall-2  lyr v 1. 73.0 77.0 73.75 111.00
node S-Wall-1  lyr v 1. 73.0 77.0 73.75 111.00
node S-Wall-0  lyr v 1. 73.0 77.0 73.75 111.00
node W-Wall    srf v 1. 73.0 77.0 73.75  98.00 0.90
node W-Wall-1  lyr v 1. 73.0 77.0 73.75  98.00
node W-Wall-0  lyr v 1. 73.0 77.0 73.75  98.00
node N-Wall    srf v 1. 73.0 77.0 73.75 111.00 0.90
node N-Wall-1  lyr v 1. 73.0 77.0 73.75 111.00
node N-Wall-0  lyr v 1. 73.0 77.0 73.75 111.00
node E-Wall    srf v 1. 73.0 77.0 73.75  98.00 0.90
node E-Wall-1  lyr v 1. 73.0 77.0 73.75  98.00
node E-Wall-0  lyr v 1. 73.0 77.0 73.75  98.00
node Floor     srf v 1. 73.0 77.0 73.75 169.97 0.90
node Floor-4   lyr v 1. 73.0 77.0 73.75 169.97 0.90
node Floor-3   lyr v 1. 73.0 77.0 73.75 169.97 0.90
node Floor-2   lyr v 1. 73.0 77.0 73.75 169.97 0.90
node Floor-1   lyr v 1. 73.0 77.0 73.75 169.97 0.90
node RmAir     air c 1. 73.0 77.0 73.75 1360.0  RoomTemp  RoomTemp
```

```
element DryWall    mat  0.0521 0.093 50.0 0.26 0.0
element FiberGlass mat  0.146  0.026 0.53 0.2  0.0
element Concrete   mat  0.0521 1.0   140. 0.22 0.0
element Carpet     mat  0.0728 0.035 40.  0.2  0.0
element AccTile    mat  0.0417 0.035 23.  0.2  0.0
element hpl_ceil  hcv 0.16 8.0
0.0 0.10 0.33 0.0 0.22 0.33
element hpl_wall  hcv 0.54 8.0
0.0 0.19 0.33 0.0 0.19 0.33
element hpl_floor hcv 0.71 8.0
0.0 0.22 0.33 0.0 0.10 0.33
element hpl_hous  hcv 1.40 8.0
0.0 0.22 0.33 0.0 0.10 0.33
element hlm_hous  hcv 0.0 0.0
0.0 0.10 0.33 0.0 0.22 0.33
element hlm_tube  hcv 0.0 0.0
0.0 0.19 0.33 0.0 0.19 0.33
element hlm_lens  hcv 0.0 0.0
0.0 0.22 0.33 0.0 0.10 0.33
element hrm_ceil  hcv 2.01 36.9
0.0 0.10 0.33 0.0 0.22 0.33
element hrm_wall  hcv 0.74 14.3
0.0 0.19 0.33 0.0 0.19 0.33
element hrm_floor hcv 0.62 8.24
0.0 0.22 0.33 0.0 0.10 0.33
element tube  lmp  48.0  3200.  372.  1.57  0.90  0.64  .2  11
      0.0         0.661        0.022
     20.0         0.672        0.068    (Ref: IES Lighting Handbook,
     40.0         0.704        0.165     Ref Volume, 1984, Fig 8-34)
     60.0         0.818        0.476
     70.0         0.894        0.701
     80.0         0.971        0.865
     90.0         0.999        0.960
    100.0         0.965        0.995
    120.0         0.858        0.850
    140.0         0.721        0.697
    215.0         0.000        0.000
element flow-tot cfr 200.     flow: plenum - load
element flow-rp  cfr 200.     flow: room - plenum
element flow-rl  cfr 000.     flow: room - luminaire - plenum

link Flow-rp   afp  flow-rp     RmAir    PlAir   flow
link Flow-rl   afp  flow-rl     RmAir    LmAir   flow
link Flow-lp   afp  flow-rl     LmAir    PlAir   flow
link Flow-pl   afp  flow-tot    PlAir    PlLoad  flow
link S-Plen-2  cnd  DryWall     S-Plenum S-Plen-2
link S-Plen-1  cnd  DryWall     S-Plen-2 S-Plen-1
link S-Plen-0  cnd  FiberGlass  S-Plen-1 S-Plen-0
link W-Plen-1  cnd  DryWall     W-Plenum W-Plen-1
link W-Plen-0  cnd  FiberGlass  W-Plen-1 W-Plen-0
link N-Plen-1  cnd  DryWall     N-Plenum N-Plen-1
link N-Plen-0  cnd  FiberGlass  N-Plen-1 N-Plen-0
link E-Plen-1  cnd  DryWall     E-Plenum E-Plen-1
```

```
link E-Plen-0  cnd  FiberGlass  E-Plen-1 E-Plen-0
link Ceiling   cnd  AccTile     PlenumSC SspCeil
link Undsid-c  cnv  hpl_ceil     UnderSide PlAir Flow-pl  420.  200.
link S-Plen-c  cnv  hpl_wall     S-Plenum  PlAir Flow-pl  420.  200.
link W-Plen-c  cnv  hpl_wall     W-Plenum  PlAir Flow-pl  420.  200.
link N-Plen-c  cnv  hpl_wall     N-Plenum  PlAir Flow-pl  420.  200.
link E-Plen-c  cnv  hpl_wall     E-Plenum  PlAir Flow-pl  420.  200.
link C-Plen-c  cnv  hpl_floor    PlenumSC  PlAir Flow-pl  420.  200.
link H-Plen-c  cnv  hpl_hous     housing  PlAir  Flow-pl  420.  200.
link Steel-c   cnv  hpl_wall     Steel    PlAir  Flow-pl  420.  200.
link PlenRad vfm 8     data for plenum geometry
UnderSide              area: 169.9688
.000000 .066438 .055097 .068282 .054832 .367727 .046498 .341126
S-Plenum               area: 34.6875
.325547 .000000 .063638 .019546 .063338 .300087 .058326 .169518
W-Plenum               area: 30.6250
.305786 .072080 .000000 .073309 .008029 .303667 .051566 .185562
N-Plenum               area: 34.6875
.334582 .019546 .064723 .000000 .064525 .310398 .053571 .152655
E-Plenum               area: 30.6250
.304319 .071740 .008029 .073084 .000000 .303338 .051649 .187842
PlenumSC               area: 153.9688
.405940 .067606 .060401 .069929 .060335 .000000 .040425 .295364
housing                area: 29.3200
.269552 .069003 .053862 .063378 .053947 .212284 .002752 .275222
Steel                  area: 200.0000
.289903 .029401 .028414 .026476 .028763 .227384 .040348 .329311

link Luminaire lum tube  8  tubes  9.0
    switch .17 housing 8
    tubes   0.0296
    housing 0.0734
    Floor   0.493
    SspCeil 0.0269
    E-Wall  0.0925
    S-Wall  0.0965
    W-Wall  0.0959
    N-Wall  0.0922
link Lamphs-c  cnv  hlm_hous     housing  LmAir  null
link Lamptb-c  cnv  hlm_tube     tubes    LmAir  null
link Lampln-c  cnv  hlm_lens     AcrLens  LmAir  null
link LumCond1  knd   4.0  housing PlenumSC
link LumCond2  knd   4.0  housing SspCeil
link LumCond3  knd   4.0  housing tubes
link LampRad vfm 3     data for 2 tube luminaire
AcrLens                area: 1.0000 * 16
.000000 .709451 .290549
housing                area: 1.8340 * 16
.386833 .362745 .250422
tubes                  area: 0.7806 * 16
.372213 .588362 .039426

link S-Wall-2  cnd  DryWall     S-Wall   S-Wall-2
link S-Wall-1  cnd  DryWall     S-Wall-2 S-Wall-1
```

```
link S-Wall-0  cnd  FiberGlass  S-Wall-1 S-Wall-0
link W-Wall-1  cnd  DryWall     W-Wall   W-Wall-1
link W-Wall-0  cnd  FiberGlass  W-Wall-1 W-Wall-0
link N-Wall-1  cnd  DryWall     N-Wall   N-Wall-1
link N-Wall-0  cnd  FiberGlass  N-Wall-1 N-Wall-0
link E-Wall-1  cnd  DryWall     E-Wall   E-Wall-1
link E-Wall-0  cnd  FiberGlass  E-Wall-1 E-Wall-0
link Floor-4   cnd  Carpet      Floor   Floor-4
link Floor-3   cnd  Concrete    Floor-4 Floor-3
link Floor-2   cnd  Concrete    Floor-3 Floor-2
link Floor-1   cnd  Concrete    Floor-2 Floor-1
link Floor-0   cnd  Concrete    Floor-1 UnderSide
link SspCel-c  cnv  hrm_ceil     SspCeil  RmAir  Flow-pl  1360.  200.
link AcLens-c  cnv  hrm_ceil     AcrLens  RmAir  Flow-pl  1360.  200.
link S-Wall-c  cnv  hrm_wall     S-Wall   RmAir  Flow-pl  1360.  200.
link W-Wall-c  cnv  hrm_wall     W-Wall   RmAir  Flow-pl  1360.  200.
link N-Wall-c  cnv  hrm_wall     N-Wall   RmAir  Flow-pl  1360.  200.
link E-Wall-c  cnv  hrm_wall     E-Wall   RmAir  Flow-pl  1360.  200.
link Floor-c   cnv  hrm_floor    Floor    RmAir  Flow-pl  1360.  200.
link RoomRad vfm 7     data for room geometry
Floor                  area: 169.9688
.000000 .174201 .152542 .174201 .152542 .314427 .032086
S-Wall                 area: 111.0000
.266746 .000000 .154335 .157839 .154335 .241291 .025455
W-Wall                 area: 98.0000
.264566 .174808 .000000 .174808 .121254 .238852 .025713
N-Wall                 area: 111.0000
.266746 .157839 .154335 .000000 .154335 .242618 .024128
E-Wall                 area: 98.0000
.264566 .174808 .121254 .174808 .000000 .238823 .025742
SspCeil                area: 153.9688
.347101 .173953 .152028 .174909 .152009 .000000 .000000
AcrLens                area: 16.0000
.340854 .176594 .157495 .167387 .157671 .000000 .000000

times  3  120  240  720

report testitb.rpt  6  240
node  RmAir   Q  i  %10.3f
node  PlLoad  Q  i  %10.3f
link  Luminaire  Q  i  %10.3f
node  tubes   T  i  %8.3f
node  LmAir   T  i  %8.3f
node  PlAir   T  i  %8.3f

report testitb.sum  3  3600
node  RmAir   Q  s  %10.3f
node  PlLoad  Q  s  %10.3f
link  Luminaire  Q  s  %10.3f

report testitb.wls  6  240
node  Floor-4  T  i  %8.3f
node  UnderSide T i  %8.3f
node  W-Wall   T  i  %8.3f
```

```
node  W-Plenum T  i  %8.3f
node  SspCeil  T  i  %8.3f
node  PlenumSC T  i  %8.3f

display  6  3600
node  RmAir   Q  i  %10.3f
node  PlLoad  Q  i  %10.3f
link  Luminaire  Q  i  %10.3f
node  tubes   T  i  %8.3f
node  LmAir   T  i  %8.3f
node  PlAir   T  i  %8.3f

* end of data

/*subfile:  testitb.bvf  ****************************************************/
0
000/23:00:00
002/00:00:00
*

/*subfile:  testitb.def  ****************************************************/
000/23:00:00
001/00:00:00   flow 1.0
001/00:00:00   switch 1.0
004/00:00:00
*
```

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11. ABSTRACT (A 200-WORD OR LESS FACTUAL SUMMARY OF MOST SIGNIFICANT INFORMATION. IF DOCUMENT INCLUDES A SIGNIFICANT BIBLIOGRAPHY OR LITERATURE SURVEY, MENTION IT HERE.)

This report describes the initial release of the HLITE program, which simulates the thermal interaction of lighting and HVAC systems. This program was developed to extend the results of an experimental study in HVAC/lighting interaction being conducted at the National Institute of Standards and Technology (NIST). It will serve in planning future experimental test cases and in the development of algorithms that can be incorporated into larger building energy analysis programs. This interim report covers the first phase of the development of HLITE which simulates the NIST HVAC/lighting test facility. Future planned developments will expand its capabilities to larger facilities with more complete thermal interactions. The computer program is based on a simple combined explicit and implicit time integration scheme for a finite volume model which may be applicable to a much broader range of building simulations.

12. KEY WORDS (6 TO 12 ENTRIES; ALPHABETICAL ORDER; CAPITALIZE ONLY PROPER NAMES; AND SEPARATE KEY WORDS BY SEMICOLONS)

computer; energy calculation; HVAC; lighting; modeling; transient simulation

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