IMPACT OF SIMULTANEOUS SIMULATION OF BUILDINGS AND MECHANICAL SYSTEMS IN HEAT BALANCE BASED ENERGY ANALYSIS PROGRAMS ON SYSTEM RESPONSE AND CONTROL

by

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ABSTRACT

The current generation of building simulation software is based upon separate building, mechanical system, and equipment simulations. This scheme evolved primarily because of memory limitations of the computers which were used to develop the programs. Hardware advancements have eliminated some of these limitations so the separate building and system scheme needs to be reevaluated. In addition to discussing methods of introducing simultaneous building and system simulations into the BLAST program, this paper will also address new system specification and control strategy options which are made possible by the simultaneous simulation method.

BLAST currently uses a linear univariate control profile to describe the heating and cooling provided by the fan system as a function of room temperature during the loads calculation. Control profiles for each thermal zone are used to model the system response during the loads simulation. Alternatively, a combined simulation of the zone and the system determines the system output by allowing each system component to respond to changes within the zone and the outside environment. The combined simulation technique also allows modelling of systems which are impossible to represent using BLAST control profiles: for example, cooling to the zone provided by outside air ventilation. The combined simulation is accomplished by using time steps short compared with conventional hourly energy-balance based programs, but long compared with finite difference methods. In addition, the system response is allowed to lag the zone conditions by one time step. This completely eliminates iteration from the solution procedure: however, instabilities may be introduced due to the feedback between zone and system. Methods have been developed to simulate physical controllers which modify the response of system components to variable zone conditioning demands. The use of short time steps also affects the calculation of conduction transfer functions (CTF's) used to compute surface temperatures and heat fluxes. For a given construction the accuracy of CTF calculations decreases as the number of terms in the CTF series increases, due to round-off and truncation errors. This problem has been avoided by calculating the CTF series at large enough time steps to ensure accuracy and maintaining a "master" set of surface temperature and flux histories from which intermediate "temporary" histories can be interpolated to give temperatures and fluxes at the desired times.

This paper specifically discusses the results of performing a complete system simulation within the loads calculation portion of **the BLAST program** by using a shortened time step combined with lagging the system simulation. In addition, new ideas for specifying systems to take advantage of this scheme are presented along with concepts for system control.

I. INTRODUCTION

Hourly building energy analysis programs capable of annual simulations currently use either the heat balance method or the weighting factor method to simulate a building's thermal zones. In either case, such simulations are capable of providing a detailed breakdown of hourly building energy use. The Building Loads Analysis and System Thermodynamics (BLAST) program uses the heat balance method and it has been employed as a "testbed" program (Witte et. al. 1989, Taylor et. al 1990) for extensive evaluation of schemes to fully integrate the building-mechanical system simulation.

In BLAST, as with other state-of-the-art simulations using the heat balance method, the building, its air handling systems, and its equipment are simulated sequentially with no feedback. The building conditions are fed to the air handling system to determine its response, but that response is not allowed to affect the building conditions. This simulation technique works well when the system response is a well-defined function of the air temperature of the conditioned space. But in situations where the system is dependent on outside conditions and/or other parameters of the conditioned space, the lack of feedback from the system to the building can lead to unphysical results. For example, if the system provides too much cooling to a conditioned space the excess cooling is reported by BLAST as "overcooling". To the system designer, it would be far more useful to see how much below the desired temperature the zone actually went.

Witte et. al. and Taylor et. al. have demonstrated several schemes which combine the building and system portions of the simulation. Witte's approach was primarily to use iterative techniques, such as Newton-Raphson and retain the hourly nature of the simulation. Taylor et. al. have concentrated on short time step time-marching methods which eliminate iteration. Both approaches involve significant computational penalty over the standard BLAST program; however, this penalty is more than justified by the improved utility of the program output to the designer. Current work with the integrated simulation technique, and the the focus of this paper, has been directed at fully implementing the short time step "lagging with zone capacitance method in BLAST in order to develop realistic systems and system control schemes.

II. CURRENT METHOD - HOURLY ENERGY BALANCE

In the current structure of BLAST the building, the fan systems, and the plants are simulated independently in that information is passed from the loads simulation to the fan system simulation to the central plants simulation without feedback. BLAST first performs the loads simulation by computing an hourly energy balance for each zone using weather, scheduled loads (lights, people, etc.) and desired zone conditions. This energy balance is represented as follows:

$$\Sigma Q_c + \sum_{i=1}^{nsurfaces} h_i A_i (T_{si} - T_z) + \dot{m}_{inf} c_p (T_\infty - T_z) + \sum_{i=1}^{nzones} \dot{m}_i c_p (T_{zi} - T_z) + Q_{sys} = 0 \qquad (1)$$

where:

ΣQ_C = sum of the internal loads

$\sum_{i=1}^{nsurfaces} h_i A_i (T_{si} - T_z)$ = convective heat transfer from the zone surfaces

$\dot{m}_{inf} c_p (T_\infty - T_z)$ = heat transfer due to infiltration of outside air

$\sum_{i=1}^{nzones} \dot{m}_i c_p (T_{zi} - T_z)$ = heat transfer due to interzone air mixing

Q_{sys} = system output.

Internal loads occur when lighting, electrical equipment , people, etc. are present in the zone and are specified as input. Heat transfer through zone surfaces is computed from the surface convection coefficient h_i and the surface temperature T_{si}, where each surface or surface element (wall, window, door, etc.) is assumed to be isothermal. The surface temperatures are computed by performing heat balances on the inside and outside surfaces, and using conduction transfer functions to relate conditions across the surface. There has already been extensive treatment of the response factor and conduction transfer function (CTF) method used in current versions of BLAST (Hittle 1980). Sources of infiltration are doors and windows open to the outside environment, in BLAST infiltration rates are specified as input. Similarly, the mixing term represents infiltration of air from other zones in the building and is likewise specified as input. A more detailed description of the computational procedure used in BLAST can be found in the BLAST Users Manual.

Since the system is not simulated at this point Q_{sys} is computed using a control profile, which is a piecewise linear approximation of the system output as a function of zone mean air temperature (T_Z):

$$Q_{sys} = m\, T_z + b \qquad (2)$$

where m is the slope of a linear segment in the control profile and b is the segment endpoint. The desired zone temperature is achieved by using line segments with different slopes to manipulate the shape of the control profile to approximate the response of the simulated system. A generic single segment control profile is shown in figure (1).

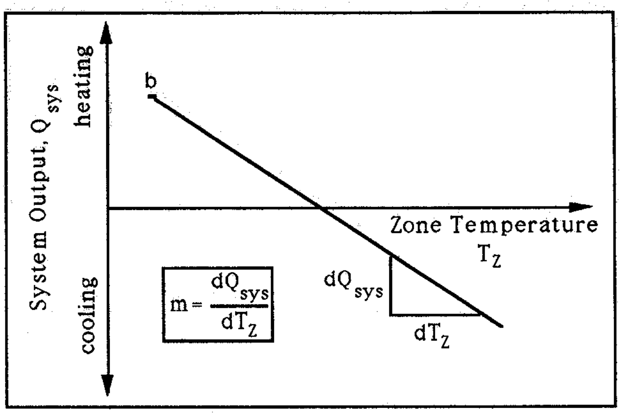

Figure 1: Generic single segment BLAST control profile

Substituting equation (2) into the zone energy balance equation and solving for the zone temperature gives:

$$T_z = \frac{\Sigma Q_c + \sum_{i=1}^{nsurfaces} h_i A_i T_{si} + \dot{m}_{inf} c_p T_\infty + \sum_{i=1}^{nzones} \dot{m}_i c_p T_{zi} + b}{\sum_{i=1}^{nsurfaces} h_i A_i + \dot{m}_{inf} c_p + \sum_{i=1}^{nzones} \dot{m}_i c_p - m} \qquad (3)$$

BLAST iterates on this equation until the change in T_Z is less than some tolerance value at which point the simulation stores the zone conditions and the system output as calculated from the control profile and goes on to the next hour. This procedure is repeated until the loads simulation is complete. The fan systems simulation then attempts to match the required Q_{sys} every hour, based on zone and outside conditions. This technique works very well when the system output is dependent on T_Z alone; however, when the system output is also a function of the outside conditions or conditions in the zone other than T_Z, a single control profile is no longer an adequate representation of the system-zone interaction. Once the fan systems simulation is complete, BLAST repeats the process for central plants.

III. METHOD OF LAGGING WITH ZONE CAPACITANCE

The method of lagging with zone capacitance uses information from previous time steps to predict system response. In this sense it can be thought of as a time marching method in which the results at a given time can be calculated directly from the results at one or more previous times without iteration. In order to preserve the stability of the simulation a shorter time step than one hour is required; therefore, some of the benefit of eliminating iterations is lost in the increased number of computations required for the same simulation time.

For most systems simulated in BLAST, it is possible to formulate the system energy provided to the zone, Q_{sys}, by using the mass flow provided by the system and the temperature of the supply air:

$$Q_{sys} = \dot{m}_{sys} c_p (T_{supply} - T_z) \tag{4}$$

Note that this expression is a function of the zone air temperature. We now substitute for Q_{sys} in the heat balance equation (1) and reformulate to include the effects of zone capacitance as in equation 5:

$$C_z \frac{dT_z}{dt} = \Sigma Q_c + \sum_{i=1}^{nsurfaces} h_i A_i (T_{si} - T_z) + \dot{m}_{inf} c_p (T_\infty - T_z) + \sum_{i=1}^{nzones} \dot{m}_i c_p (T_{zi} - T_z) + \dot{m}_{sys} c_p (T_{supply} - T_z) \tag{5}$$

The sum of zone loads and system output now represents the change in energy stored in the zone. Typically the capacitance term would be primarily due to the zone air; however, other fast responding thermal masses within the zone could be included. The zone energy storage is given by the product of the zone capacitance and the first derivative of the zone air temperature, assuming that temperatures of zone air and fast responding masses are equal.

The derivative term can be computed using finite difference approximations such as:

$$\left.\frac{dT_z}{dt}\right|_t \approx (\delta t)^{-1} \left(T_z^t - T_z^{t-\delta t} \right) + O(\delta t) \tag{6}$$

which is first order accurate in time and is more commonly known as the Euler formula. The use of finite differences in a long time simulation such as BLAST may cause some concern due to the build-up of truncation error, especially when the finite difference approximation is of low order. However, the cyclic nature of the simulations will cause truncation errors to cancel over one cycle so that there will be no accumulation over the long term (Walton 1990, personal communication). The finite difference expression for the zone air temperature using the Euler approximation is given by:

$$C_z \frac{T_z^t - T_z^{t-\delta t}}{\delta t} = \left(\begin{array}{c} \Sigma Q_c + \sum_{i=1}^{nsurfaces} h_i A_i (T_{si} - T_z) \\ + \dot{m}_{inf} c_p (T_\infty - T_z) + \sum_{i=1}^{nzones} \dot{m}_i c_p (T_{zi} - T_z) \\ + \dot{m}_{sys} c_p (T_{supply} - T_z) \end{array} \right)^{t-\delta t} \tag{7}$$

This equation may be modified by grouping all the terms containing the zone air temperature on one side of the equation and the remaining terms on the other:

$$C_z \frac{T_z^t - T_z^{t-\delta t}}{\delta t} + \sum_{i=1}^{nsurfaces} h_i A_i T_z^t + \dot{m}_{inf} c_p T_z^t + \sum_{i=1}^{nzones} \dot{m}_i c_p T_z^t + \dot{m}_{sys} c_p T_z^t = \left(\Sigma Q_c + \sum_{i=1}^{nsurfaces} h_i A_i T_{si} + \dot{m}_{inf} c_p T_\infty + \sum_{i=1}^{nzones} \dot{m}_i c_p T_{zi} + \dot{m}_{sys} c_p T_{supply} \right)^{t-\delta t} \tag{8}$$

Thus the explicit appearance of the zone air temperature is removed from one side of the equation. Dividing through by the coefficient of T_z gives an energy balance equation which includes the effects of zone capacitance:

$$T_z^t = \frac{\left(\frac{C_z}{\delta t} T_z + \Sigma Q_c + \sum_{i=1}^{nsurfaces} h_i A_i T_{si} + \dot{m}_{inf} c_p T_\infty + \sum_{i=1}^{nzones} \dot{m}_i c_p T_{zi} + \dot{m}_{sys} c_p T_{supply} \right)^{t-\delta t}}{\left(\frac{C_z}{\delta t} + \sum_{i=1}^{nsurfaces} h_i A_i + \dot{m}_{inf} c_p + \sum_{i=1}^{nzones} \dot{m}_i c_p + \dot{m}_{sys} c_p \right)} \tag{9}$$

In addition to equation (6) which resulted in the formulation given by equation (9), there are numerous ways of expressing the first derivative of the temperature in finite difference form. By using Taylor series expansion methods it is possible to develop higher order expressions for the first derivative with corresponding higher order truncation errors. In our investigations we have found that a third order finite difference approximations gives the best results (Taylor 1990):

$$\left.\frac{dT_z}{dt}\right|_t \approx (\delta t)^{-1} \left(\frac{11}{6} T_z^t - 3T_z^{t-\delta t} + \frac{3}{2} T_z^{t-2\delta t} - \frac{1}{3} T_z^{t-3\delta t} \right) + O(\delta t^3) \tag{10}$$

Furthermore, we have also shown that time steps of 0.1 to 0.25 hour are adequate to guarantee stability for most cases where the system response is well behaved; however, system control schemes must also be stable to ensure overall stability of the simulation.

IV. OPTIONS FOR SYSTEM CONTROL

In the previous section we discussed the formulation of a new heat balance equation in which the updated zone temperature was calculated by removing its explicit dependence from the right hand side of equation (5). The right hand side still contains implicit dependencies on the zone temperature and this is nowhere more apparent than in the system term. The implicit zone temperature dependence of the system is generated through the system control scheme which samples the zone temperature to determine the proper mode of system operation to maintain the desired zone conditions. In real buildings the control system may be a wall thermostat which samples the air temperature and sends appropriate signals to an air handling system based on whether the zone is too hot or too cold. It would seem that modelling such a controller would seem to be a rather trivial exercise; however, the real controller has the advantage of being able to continuously sample zone conditions, and thus update system response on a time scale much shorter than any characteristic time of the system or zone. Thus the feedback between zone and system generally results in stable zone conditions and system operation. On the other hand, the numerical model is only able to sample zone conditions every time step which, in the interest of minimizing computation time, is generally of the order of, or longer than, the characteristic times of the system or zones, except in the case of small system capacity in relation to zone volume. This situation has the potential for unstable feedback between zone and system and could result in an oscillatory or diverging solution.

In implementing the new heat balance method in BLAST we have considered several system control strategies with our primary goals being numerical stability, realism, and applicability to current and future systems modelled by BLAST. The method selected for full implementation in BLAST takes advantage of the fact that, unlike the real controller, the computational model "knows" how much energy is entering or leaving the zone as a function of zone temperature. This quantity can be expressed as:

$$Q_{load} = \Sigma Q_c + \sum_{i=1}^{nsurfaces} h_i A_i (T_{si} - T_z) + \dot{m}_{inf} c_p (T_\infty - T_z) + \sum_{i=1}^{nzones} \dot{m}_i c_p (T_{zi} - T_z) \quad (11)$$

This is just equation (5) without the system energy term and Tz is now the *desired* zone temperature which corresponds to one of the control system setpoints and is specified by the user. Now, we make the assumption that if the system can meet the zone conditioning requirements (i.e. $Q_{sys} = Q_{load}$) then it will. If the system cannot meet the zone conditioning requirements then the zone temperature adjusts itself accordingly. Equation (11) is used soley to determine the system output and once this is accomplished the zone temperature is updated using equation (9). This is the method of *predictive system energy balance*. It is, in some sense a predictor-corrector method since we first calculate the system response and then calculate its effect on the zone. The predictive system energy balance method requires that the system output be formulated as a function of the zone temperature. However, this is not a serious drawback. For example, consider a simplified single zone drawthrough system with a heating coil, a cooling coil, constant airflow, and an on/off type controller as shown schematically in figure 2.

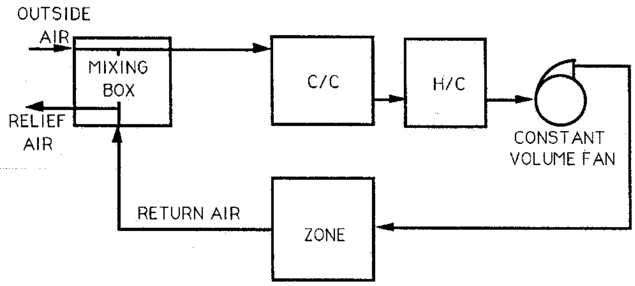

Figure 2: Simplified single zone draw through system

The cooling or heating output of such a system is:

$$Q_{sys} = \dot{m}_{sys} c_p \eta (T_{sup} - T_{z_{desired}}) \quad (12)$$

where η is taken to be the fraction of the time step that the system operates. Clearly η must be restricted to values between 0 and 1. Limits may also be placed on Q_{sys} and T_{sup} since in practice these are determined by the operating parameters of the central plant components, the effects of which we have not included. The situation is somewhat more complicated for the simplified variable air volume (VAV) system, shown in figure 3, where the supply air temperature as well as the supply air volume are continuously variable over a specified range of zone temperatures as shown in figure 4.

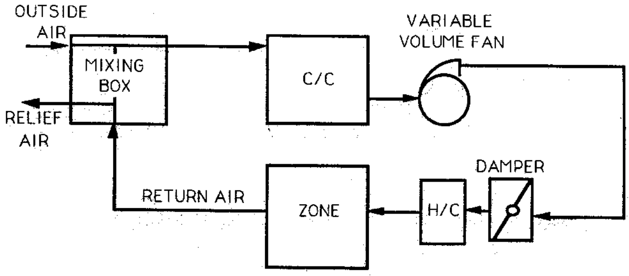

Figure 3: Simplified variable volume system

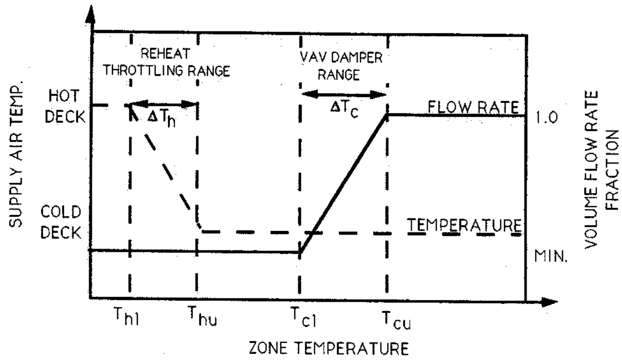

Figure 4: Idealized variable volume system operation

For the VAV system, the zone temperature can be expected to vary within the damper range or reheat throttling range depending upon whether the system is heating or cooling. This means that the desired zone temperature is also a variable and must be calculated in order to determine the system output. We begin this calculation by making the following definitions:

$$Q_{abs} = \Sigma Q_c + \sum_{i=1}^{nsurfaces} h_i A_i T_{si} + \dot{m}_{inf} c_p T_\infty + \sum_{i=1}^{nzones} \dot{m}_i c_p T_{zi} \quad (13)$$

$$Q_{coef} = \sum_{i=1}^{nsurfaces} h_i A_i + \dot{m}_{inf} c_p + \sum_{i=1}^{nzones} \dot{m}_i c_p \quad (14)$$

which are derived respectively from the numerator and denominator of equation (3) with the system related terms omitted. Note that these expressions do note include the effects of zone capacitance.

When cooling, the VAV system is designed to operate with constant supply air temperature and variable supply air volume. The volume air fraction normalized to the maximum flow rate is given by:

$$\eta_c = \eta_{c\,min} + (1 - \eta_{c\,min}) \left(\frac{T_z - T_{cl}}{\Delta T_c} \right); \quad \eta_{c\,min} \le \eta_c \le 1.0 \quad (15)$$

Conversely, when heating is required the VAV becomes a constant volume flow rate system with a variable supply air temperature which can be related directly to the energy output of the reheat coil. The energy output of the reheater normalized to the maximum coil output is:

$$\eta_h = \left(\frac{T_{hu} - T_z}{\Delta T_h} \right); \quad 0.0 \le \eta_h \le 1.0 \quad (16)$$

The VAV system output to the zone can now be written in terms of η_c and η_h as follows:

$$Q_{sys,\,heat} = \eta_h\, Q_{h/c,\,max} + C_p\, \rho\, \dot{V}_{min}\,(T_{cold\,deck} - T_z) \tag{17}$$

$$Q_{sys,\,cool} = C_p\, \rho\, \eta_c\, \dot{V}\,(T_{cold\,deck} - T_z) \tag{18}$$

Equating the system output to the load as given by equation (11) and using the definitions of η_c and η_h we can derive expressions for the predicted zone temperature:

$$T_{z,\,pred,\,heat} = \frac{\dfrac{Q_{h/c,\,max}\;T_{hu}}{\Delta T_h} + Q_{abs} + C_p\,\rho\,\dot{V}_{min}\,T_{cold\,deck}}{\dfrac{Q_{h/c,\,max}}{\Delta T_h} + C_p\,\rho\,\dot{V}_{min} + Q_{coef}} \tag{19}$$

$$T_{z,\,pred,\,cool} = \frac{B_1 + \sqrt{B_1^2 + B_2}}{2} \tag{20}$$

where,

$$B_1 = T_{cold\,deck} + T_{cl} - \frac{\eta_{c,\,min} - C_2}{C_1}$$
$$B_2 = 4\left(\frac{C_3}{C_1} + T_{cold\,deck}\left(\frac{\eta_{c,\,min}}{C_1} - T_{cl}\right)\right) \tag{21}$$

and,

$$C_1 = \frac{1 - \eta_{c,\,min}}{\Delta T_c}\,, \quad C_2 = \frac{Q_{coef}}{C_p\,\rho\,\dot{V}_{max}}\,, \quad C_3 = \frac{Q_{abs}}{C_p\,\rho\,\dot{V}_{max}} \tag{22}$$

Once the predicted zone temperature is calculated, the system response is determined. When cooling is selected the system supply air temperature is constant and the volume flow rate is given by:

$$\dot{V}_{supply} = \eta_c \dot{V}_{max} \tag{23}$$

When heating is selected the system provides air at the minimum volume flow rate and at a temperature given by:

$$T_{supply} = T_{cold\,deck} + \frac{\eta_h\, Q_{h/c,\,max}}{C_p\,\rho\,\dot{V}_{min}} \tag{24}$$

With the supply air flow rate and temperature known, the updated zone temperature can now be calculated by substitution of these quantities into equation (9).

V. CALCULATION OF WALL CONDUCTION USING CTF'S AT SMALL TIME STEPS

In a program such as BLAST, conduction transfer functions are an efficient method to compute surface heat transfer and temperature information since they eliminate the need to know what is happening within the surface. However, as our investigations into short time step computational methods for the zone/system interactions progressed we discovered that the conduction transfer function series, used to calculate transient heat conduction through zone surfaces, become progressively more unstable as the time step is decreased. Eventually, this instability causes the entire simulation to diverge. This phenomenon was most apparent for heavy constructions which have long characteristic times and, correspondingly, require a larger number of terms in the CTF series expansion. This fact indicates that the problem is related to the internal accuracy of the computer and in no way an indictment of the method itself. To address this problem, we looked extensively at CTF methods which develop CTF series from finite difference approximations to the heat conduction equation (Meyers 1980, Seem 1987). Although Seem's method did give better accuracy and stability at short time steps than the current BLAST technique, the method still had difficulty computing stable CTF series for time steps of 1/4 hour and smaller for the heaviest constructions in the BLAST library.

In BLAST it is required to know the inside and outside surface temperatures and fluxes for all the surfaces which enclose each zone. The CTF method further dictates that these quantities be retained for several previous time steps from the current time to form a time history series. However, a given CTF series is applicable only to the time step for which it was initially computed; that is, a CTF series computed for a one hour time step takes information at t hours, t-1 hours, t-2 hours, etc and computes new conditions at t+1 hours. As time progresses the oldest history term is dropped and the whole series moves back one time step to allow the newest values, those at t+1 hours, to be added to the series. Implicit in this process is that the actual histories are continous functions of time between the discrete points that are retained, but there is no direct way to compute information at these intermediate times. Essentially, the series of temperature and flux histories are out of phase with these points. It is therefore not unreasonable to suggest that intermediate points be determined by shifting the phase of the temperature and flux histories by only a fraction of a time step. This would allow a CTF series computed for a time step Δt, to be used to compute information at times $t+\Delta t/2$, $t+\Delta t/3$, $t+\Delta t/4$, or any other arbitrary fraction of the time step. In practice there are several ways of doing this as shown in figures 5, 6, and 7.

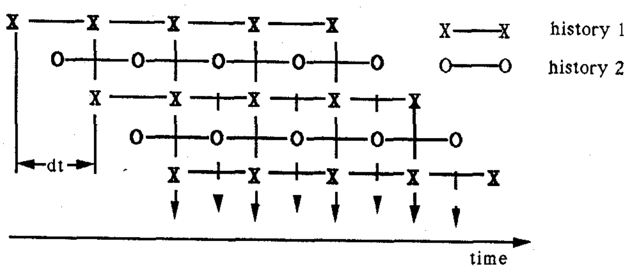

Figure 5: Multiple,staggered time history scheme

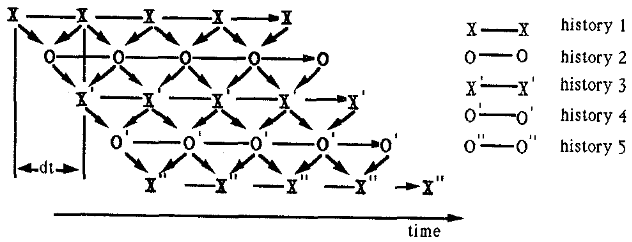

Figure 6: Sequential interpolation of new histories

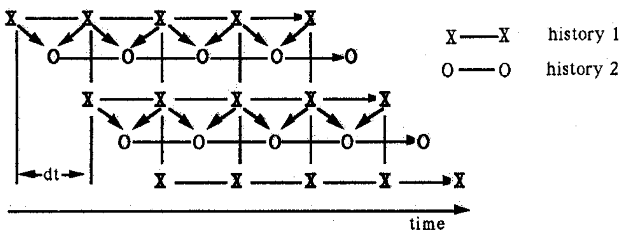

Figure 7: Master history with interpolation

The first method, shown in figure 5, maintains two sets of histories out of phase with each other by 1/2 time step, which would be the smallest convenient time step at which the CTF series is stable. Calculations of desired quantities use each set of histories alternately. This method has the advantage of requiring no interpolation, however, if the smallest stable time step is large compared to the desired time step, large amounts of storage are required for all the sets of histories.

The second method, shown in figure 6, is an interpolation method where each history used is interpolated from the previous history set. Permanent storage is thus only required for one set of temperature and flux histories. The drawback of this method is that the interpolation process smooths out the the information contained in the histories so that when time has advanced to the point that the current history is in phase with a previous history the information contained at concurrent times will be different. The net effect of this method is to change past information which is unacceptable from a physical point of view.

The final method, shown in figure 7, is something of a hybrid of the previous two methods in that one "master" history set is maintained for all time, and when information is needed at intermediate time steps the required history series is interpolated from the master. This method has proved to be the best of the three options in practice and has subsequently been incorporated into a development version of the BLAST program along with Seem's procedure for calculating CTF series.

VI. IMPLEMENTATION OF NEW METHODS AND TEST CASES

A special development version of BLAST has been created which incorporates the third order lagging method with zone capacitance and Seem's method of generating conduction transfer functions along with the "master history" interpolation scheme. In addition, we have developed entirely new system simulation routines which use the predictive system energy balance scheme. However, we have not as yet, incorporated all the complexity and sophistication of the BLAST system routines in the new code.

The test case "building" used in evaluating all new methods for this paper consists of a single 20'x20'x10' zone with:

walls - 4" concrete, 3/4" plaster board walls
slab on grade floor - 8" concrete and 12" earth
roof - 1/2" stone, 3/8" felt, 1" insulation, and 2" concrete.

The building was simulated for a Chicago, Illinois summer design day, which has daily highs of 91 F (32.8 C) and lows of 68 F (20 C). Additionally, a 5 kBtu electrical load was imposed on the building from 7 a.m. to 5 p.m. The electrical load increases the cooling requirements of the zone and is a more severe test of the simulation techniques since it acts as an extra forcing function on the system response.

Strict quantitative comparisons between outputs from BLAST and our development code are not, in general, possible, due to the fact that BLAST simulates the zone loads and systems separately. However, we have been able to generate roughly equivalent VAV systems for quantitative comparison. In addition a simplified single zone draw through system has been extensively tested, as has outside air ventilation. This is currently impossible to do with BLAST since there is no way to generate a realistic control profile for outside air ventilation.

VII. RESULTS AND COMPARISONS WITH BLAST

Our first goal is to demonstrate the stability of the predictive energy balance method for system control, combined with the lagging with zone capacitance method. Figures 9 and 10 shows the results of simulating a single zone draw through system conditioning the zone described in the previous section. In figure 9, the zone temperature is plotted as a function of time for time step of 1/4 and 1 hour. There is very good agreement between the two cases and no sign of oscillations in the solution, even at the one hour time step.

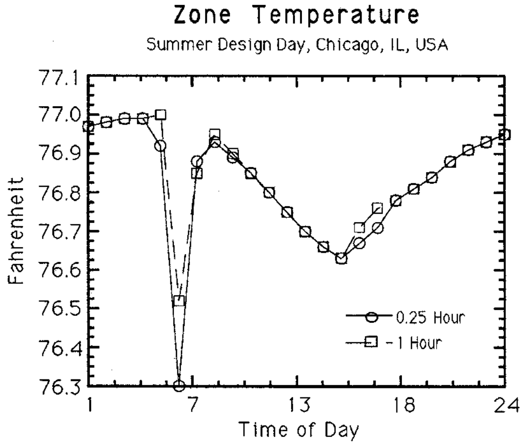

Figure 9: Daily Zone Temperature History for a Single Zone Draw Through System for 1/4 Hour and 1 Hour Time Steps

The cooling coil output, which is the difference between the zone supply air enthalpy and the cooling coil inlet air enthalpy, shows similarly good agreement as indicated in figure 10. Figures 9 and 10 indicate that under the predictive system energy balance method, guaranteeing the stability of the system response is not a serious concern. A second question arises however, that of accuracy. In BLAST, large time steps are not a problem since the simulation iterates on the zone heat balance until a self consistent solution is obtained. In the lagging method, since no iteration to convergence occurs, zone or outside conditions changing significantly over the time step can lead to physically unreasonable results. For example, consider zone air being recirculated by a fan system. Over the course of an hour the temperature within the zone could change significantly under the influence of external conditions though the recirculated air would provide no energy input to the zone. However, in a simulation using lagging, the recirculated air would be at the temperature of the zone during the previous time step and as a result could provide anomalous conditioning to the zone. A test case was run which merely recirculated zone air and allowed the zone temperature to float under the influence of outside conditions. The lagging method was used with 1 hour and 1/4 hour time steps. As can be seen in figure 11, anomalous energy is provided to the zone at the larger time steps and represents a clearly unreal situation at the one hour time step.

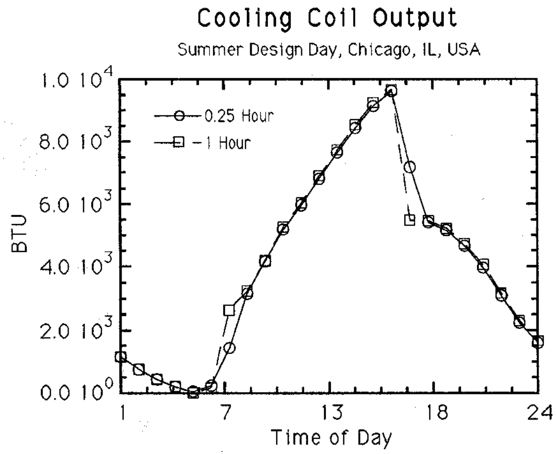

Figure 10: Daily Cooling Coil Output History for a Single Zone Draw Through System for 1/4 Hour and 1 Hour Time Steps

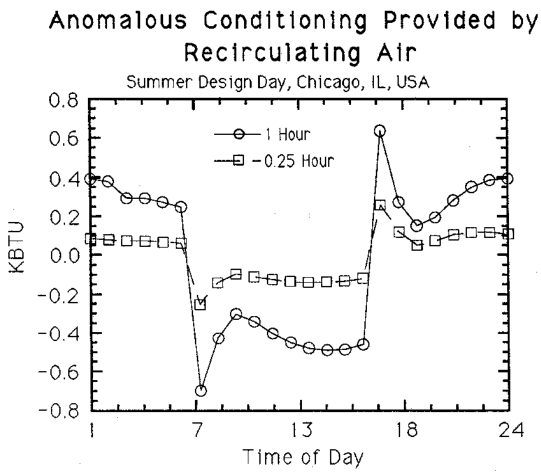

Figure 11: Anomalous cooling by recirculating air due to excessive time step

The remedy to this problem is to run at 1/4 hour time steps or shorter to minimize this effect. It should also be noted that this anomalous energy is small compared to the system energy input to the zone in most cases and averaged over the daily cycle the net contribution to the change in zone energy would be close to zero. In addition the introduction of outside air, which is required for ventilation purposes, further dilutes the effect since outside air conditions are not lagged. Therefore, accuracy of the simulation is not likely to be severely compromised.

Figure 12 shows the effect of pure ventilation of outside air on the zone temperature. Figure 13 gives the cooling provided to the zone by the outside air. Clearly, it would be undesirable to run pure ventilation given the weather in Chicago during midsummer, but the ability of the new heat balance method to model systems which BLAST cannot is clearly demonstrated. The 0.1 hour and 0.25 hour cases show excellent agreement of the zone temperatures and marginal differences in the cooling provided to the zone.

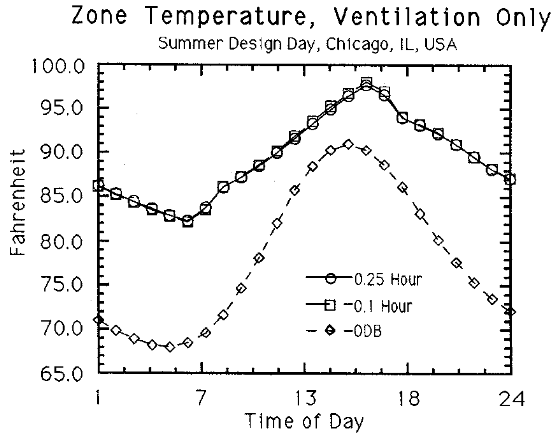

Figure 12: Daily Zone Temperature History for Outside Air Ventilation Only

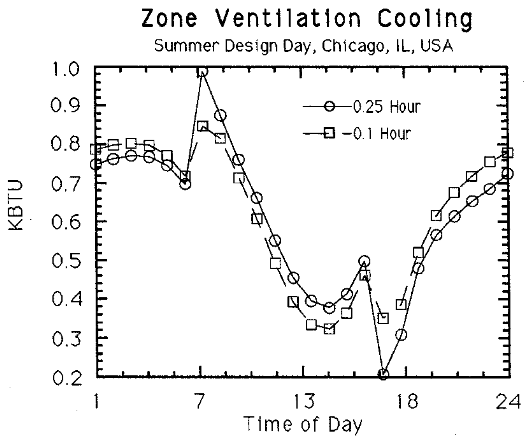

Figure 13: Outside Air Ventilative Cooling Provided to the Zone

Finally, we compare BLAST and the combined method for the zone and conditions described above and with a VAV system conditioning the zone. As was mentioned previously, the differences between the computational methods make it difficult to create identical zone temperature controllers to allow strictly quantitative comparisons. As shown in figures 14 and 15, qualitatively the trends shown in the zone temperature and cooling coil output histories are very similar though the actual numbers differ somewhat.

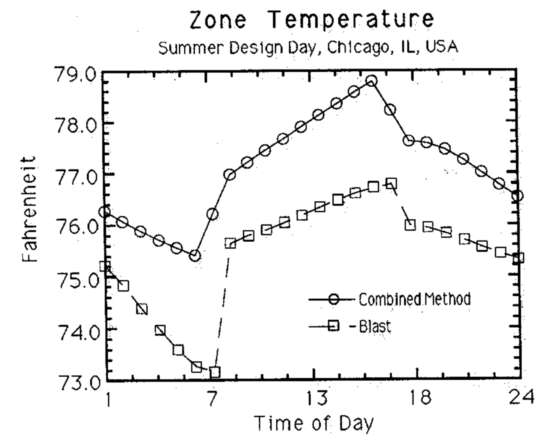

Figure 14: Comparison of BLAST and Combined Loads and Systems Method Cooling Coil Output for a Summer Design Day

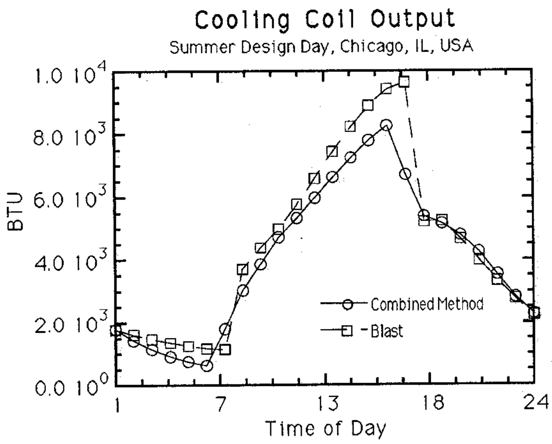

Figure 15: Comparison of BLAST and Combined Loads and Systems Method Zone Temperature for a Summer Design Day

VIII. CONCLUSIONS

During the course of this research we have explored several options for controlling system simulations, when these are a part of whole building simulations. We have demonstrated that the method of predictive system energy balance combined with the lagging with zone capacitance method for solving the zone energy balance is a viable technique. Our results show that the method is stable under a wide range of simulation conditions and allows great flexibility in selecting an appropriate time step. The one caveat to this statement concerns the simulation of pure ventilation of outside air. Although such a simulation is stable for time steps of one hour or more, such large time steps are not recommended since significant anomalous cooling can be obtained from recirculated air. In order to minimze this effect, time step of one hour or less should be utilised.

A further implication of the large time steps allowed by the predictive system energy balance scheme is that computation time can be reduced over schemes attempting to simulate real time control. This is an important point for most users of BLAST and other building simulation programs which are PC based. A new version of BLAST which incorporates the combined simulation will not require current BLAST users to upgrade their hardware. Preliminary results indicate that the principal penalty of the new scheme will be an increase in computation time over BLAST but with substantially reduced memory requirements since there is no need to store zone loads information before passing it on to the system simulation.

A secondary conclusion from this work is that it is possible to calculate wall surface temperature and flux information at time steps intermediate to those which the CTF series was calculated for by interpolating new temperature an flux histories from the current temperature and flux histories. This has proved most beneficial to our research since it has enabled us to retain the CTF method. Other methods, such as a finite difference solution to the heat conduction equation would have resulted in a significant increase in computation time and memory requirements. In addition the interpolation scheme will allow the use of an adaptive time step building simulation, wherein the time step is allowed to be large when conditions are relatively constant and is shortened when conditions are changing more rapidly.

Work with our development version of BLAST is continuing with an emphasis on bringing the code up to release standards. This entails major rework of internal record keeping, new system development, and optimization. The next major technical question will be completing the feedback loop from the central plants simulation to systems in order to generate a self-consistent simulation for an entire building.

IX. REFERENCES

BLAST 3.0 Users Manual, BLAST Support Office. University of Illinois at Urbana-Champaign, 1986.

Hittle, D. C., "Calculating Heating and Cooling Loads Using the Frequency Response of Multilayered Slabs," Ph. D. Thesis, University of Illinois, 1980.

Meyers, G. E., "Long-Time Solutions to Heat Conduction Transients with Time Dependent Inputs," Journal of Heat Transfer, vol. 102, Feb 1980, pp 115-120.

Seem, J. E., "Modeling of Heat Transfer in Buildings," PhD Thesis, University of Wisconsin-Madison, 1987.

Taylor, R. D., C. O. Pedersen, L. Lawrie, "Simultaneous Simulation of Buildings and Mechanical Systems in Heat Balance Based Energy Analysis Programs," Proceedings of the 3rd International Conference on System Simulation in Buildings, Liege, Belgium, December 3-5, 1990.

Witte, M. J., C. O. Pedersen, and J. D. Spitler, "Techniques for simultaneous simulation of buildings and mechanical systems in heat balance based energy analysis programs", Building Simulations '89, IBPSA, Vancouver, B.C., June 1989.