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Simulation of a Large Office Building System Using the HVACSIM+ Program

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ABSTRACT

A large office building system located in Gaithersburg, MD, was simulated using the HVACSIM+ computer program. A typical floor of this 11-story building was selected and divided into four zones, with one air-handling unit serving each zone. Dynamic interactions between the building zones and the HVAC and control system were studied for several different control strategies during the cooling season. Simulations were performed using the building shell and zone models along with the air handler and control system models. Simulation results are presented and compared with experimental measurements. The effects of three different control schemes on energy consumption are compared with each other. These schemes are: the start/stop control without purging cycle, the start/stop control with purging, and continuous operation.

INTRODUCTION

A large office building system—which includes the building shell, HVAC systems, and controls—was simulated using a nonproprietary building system and equipment simulation program, HVACSIM+. The simulation program was developed at the National Institute of Standards and Technology (formerly National Bureau of Standards). Simple demonstration simulations using this program were carried out by Hill (1985) and Clark et al. (1985). Recently, Syed (1987) simulated a library building with constant supply air flow rates. A general overview of HVACSIM+ was presented by Park et al. (1985). Details of this program can be found in the reports by Clark (1985), Clark and May (1985), and Park et al. (1986).

DESCRIPTION OF BUILDING SHELL AND HVAC SYSTEM

The building used for the simulation is an 11-story office building that serves as the administration building of the National Institute of Standards and Technology in Gaithersburg, MD. The building is 49.7 m (163 ft) high (excluding the bulkhead on the roof), 15 m (48 ft, 11 in) wide, and 67 m (220 ft) long. The reinforced concrete structure is enclosed by gray face bricks, insulated porcelain steel panels, and glass windows. Extended aluminum enclosures, located on both the south and north outside walls, cover the concrete columns and the supply air ducts that originate from the air-handling units located on the mezzanine floor of the building. Figure 1 is a photograph of the building.

Each floor area is 867 m^2 (9332 ft^2) and the height of the ceiling is 3.1 m (10 ft, 2 in). The second through eleventh floors are served by four air-handling units. Four service zones can be defined based on their supply air distribution. Supply air enters into the zone passing through a hot water reheat unit that is connected to the supply air duct column. Only two of the four return air ducts serve each floor. Two ducts among the four return air ducts are used for the second through sixth floors, and the remaining two ducts serve the seventh through eleventh floors. Each return air duct is connected to an air-handling unit.

Figure 1

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ficients were calculated for the exposed eastern or western wall, the exposed southern or northern wall, the glass window, the ceiling, the floor, and the interior wall that separated the zones. The boundary data file used in simulations of this study contained the information for the internal thermal load and the operating conditions of fans, dampers, and cooling coils with respect to time. Due to the fact that a large step change of variables in the boundary data file usually induced an instability in the simulation, the large step change at a certain time was approximated by small step-wise changes with smaller increments.

Modification of HVACSIM +

Some source code of the original version of HVACSIM+ was changed to make the program capable of handling the large number of components required for the simulation of the NIST administration building system. Coding errors, especially in HVACGEN, were corrected as well, and other modifications were made as necessary. More TYPEn subroutines were also written. They were TYPE30, TYPE33, TYPE34, TYPE35, and TYPE39 for cooling coil, moist air mixing dampers and merge, multiplier, mean values of temperatures and humidity ratios, and control algorithm of EMCS.

The two constant values given in the PARAMETER statement were changed for the simulations appearing in this paper. The changed values were as follows:

MAXDEQ (Maximum number of differential equations in the simulation) = 90
MAXPAR (Maximum number of Unit parameters in the simulation) = 120

The current version of HVACSIM + contains all the corrections and modifications.

Execution of Main Program

The main simulation program, MODSIM, was compiled using an optimized fortran compiler and linked with a special option on a 32-bit mini-computer with 48 MByte disk storage. The special option allowed the program execution to continue even when underflow or overflow error occurred. When step changes of some state variables were large, the convergence of solutions became difficult. Many underflow errors occurred, and the user-supplied minimum time step was used over and over again until a solution converged. To solve a set of simultaneous equations, MODSIM called the equation-solver routine, which uses the Newton-Gauss method. With this method, a good guess of initial conditions is essential to obtain convergence. Underflow or overflow errors may be unavoidable, especially when there are large step changes of state variables listed in the boundary data file.

Simulations were performed in two steps. In the first step, only the building shell portion was simulated for a 24-hour period with a time interval of 15 minutes. The resulting state variables were stored in the initialization file for the next simulation. This building shell simulation was needed to initialize the building's inner surface temperature and heat flux histories, which were then saved in an array, called Saved, in the building surface component subroutine (TYPE51). The execution time of this kind of simulation typically took about seven minutes on a minicomputer.

The second step in the simulation was carried out using the initialization file produced by the first step. In this stage, all component models were activated and thus huge amounts of outputs were generated for typical three-day simulations. The execution time of the second step simulation depended on model setup and boundary conditions, and ranged from approximately 7 to 28 hours for a three-day simulation.

Evaluation of Simulation Outputs

As shown in Figure 7, the simulation output files are the summary output file, the raw output data file, and the initialization file. The summary output file contains information from the simulation work file, weather data file, and the values of state variables at a fixed time interval that was assigned as the Reported time in the simulation work file. In addition, mnemonics for the Reported variables are included in the file. The raw output data file produced by the original MODSIM included the simulation time and the values of the state variables at each simulation time step. Because of the excess amount of outputs resulting from small time step increments in conjunction with large set-

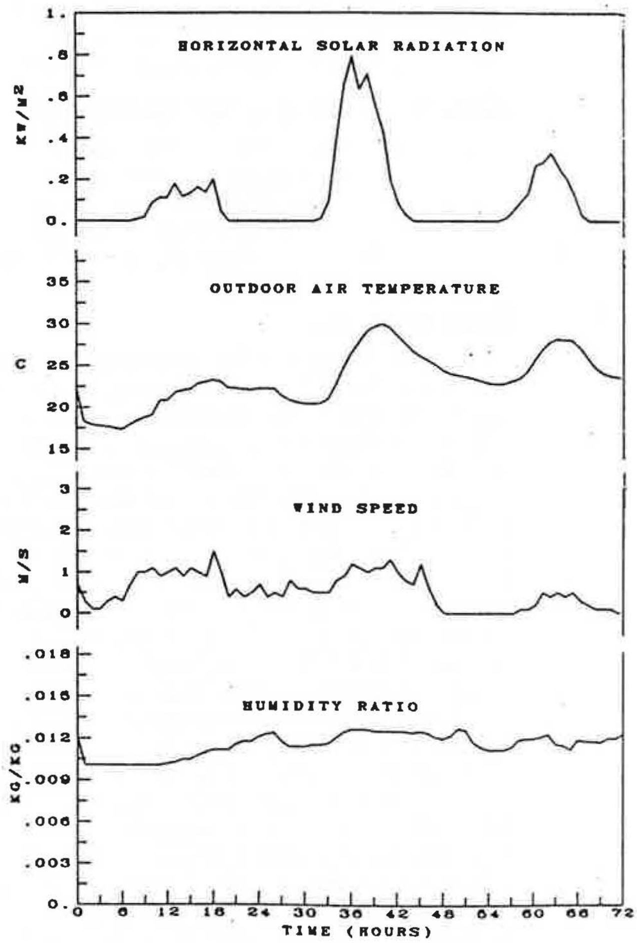

Figure 8 *Measured weather data of Gaithersburg, MD (Sept. 22-24, 1986)*

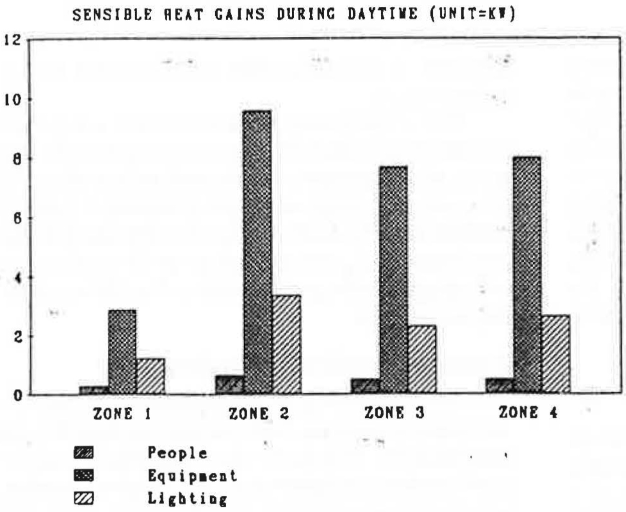

Figure 9 *Estimated sensible heat gains from internal loads during office hours*

point changes in the simulations of interest, the MODSIM program was modified to store only the outputs, if desired, at the fixed time interval used for the summary output file. A fixed time interval of 15 minutes was chosen for saving the raw output data in a file.

By using the SORTSB program the raw data file was sorted Superblock by Superblock. The sorted outputs were then plotted and the results were evaluated.

SIMULATION RESULTS AND DISCUSSION

Simulations were performed for model verification and comparisons were made for three different control strategies: continuous operation of fans and cooling coils of HVAC systems, start/stop control without nighttime purging, and start/stop control with nighttime purging.

Model Verification

Simulations for the NIST administration building were performed to verify the model. The weather data file used was created from the measurement of the outdoor air dry-bulb temperature, humidity ratio, wind speed, and horizontal total solar radiation at the NIST site from September 22, 1986 to September 24, 1986 (shown in Figure 8). The sensible and latent heat gains from people, equipment, and lighting in the zones were accounted for. Figure 9 depicts the estimated sensible heat gains during regular office working hours (8:00 a.m.- 5:00 p.m.). Only one-tenth of the entire building's internal load appears in Figure 9, which was based upon the floor areas and the number of the occupants as listed in the NIST telephone directory.

The control scheme used in the verification simulation was the start/stop control without nighttime purging. The supply and return air fans were turned on in the early morning of each working day and turned off at a certain time after working hours. On the basis of the measured supply air temperatures of air-handling units, the start time was 4:00 a.m. each day, while the stop time was 6:00 p.m. on the first day (September 22) and 11:00 p.m. on the other days (September 23 and 24). It is worthwhile to note that the start/stop control to the HVAC system of the NIST administration building was carried out manually by maintenance personnel. For each air-handling unit, the cooling coil was assumed to be active only if the fans operated at full speed.

The cooling coil valve controlling the chilled water flow rate was operated by a pneumatic controller. Its setpoint was reset on zone demand. The summer mode reset schedule for air-handling unit 3 (AHU 3) was as follows: if the zone temperature was greater than 25.3°C (77.5°F), the supply air temperature was set to 5.5°C (41.9°F) by the controller. When the zone air temperature was lower than 24.2°C (75.6°F), then the setpoint of 14.5°C (58.1°F) was selected. Between the lower and upper limits of the zone temperature, a linear change of the setpoint was used with respect to the zone air temperature.

In the simulation, the control of dampers followed a simple dry-bulb economizer algorithm. For AHU 3, the following condition was imposed: If the outdoor air dry-bulb temperature was greater than 16.7°C (62.1°F) or less than 5.5°C (41.9°F), then the damper openings were set to a minimum value. If the outside temperature was in the range between 14.5°C (58.1°F) and 16.7°C (62.1°F), the maximum damper openings were used. When the outdoor air temperature was greater than or equal to 5.5°C (41.9°F)

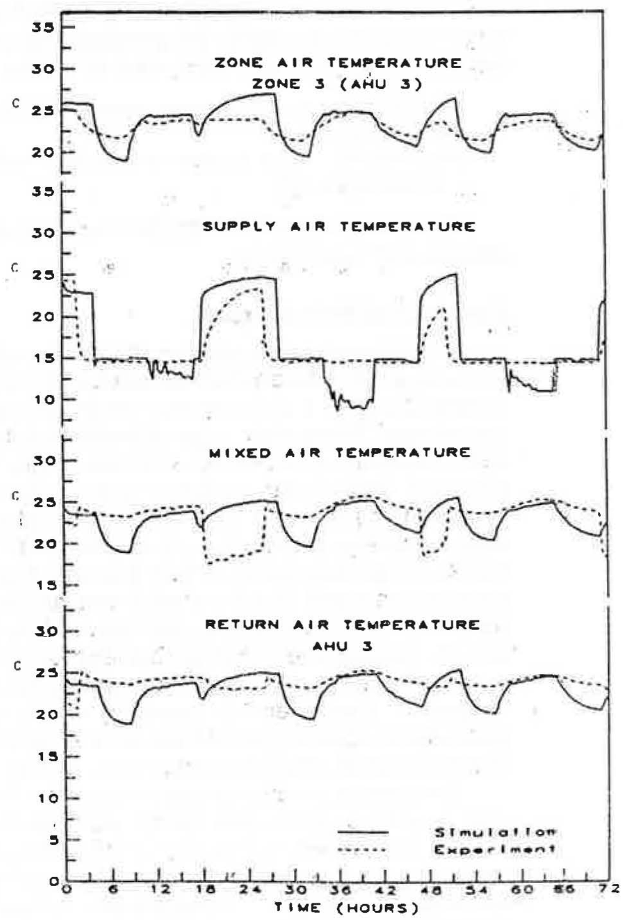

Figure 10 *Air temperatures of AHU 3 and Zone 3*

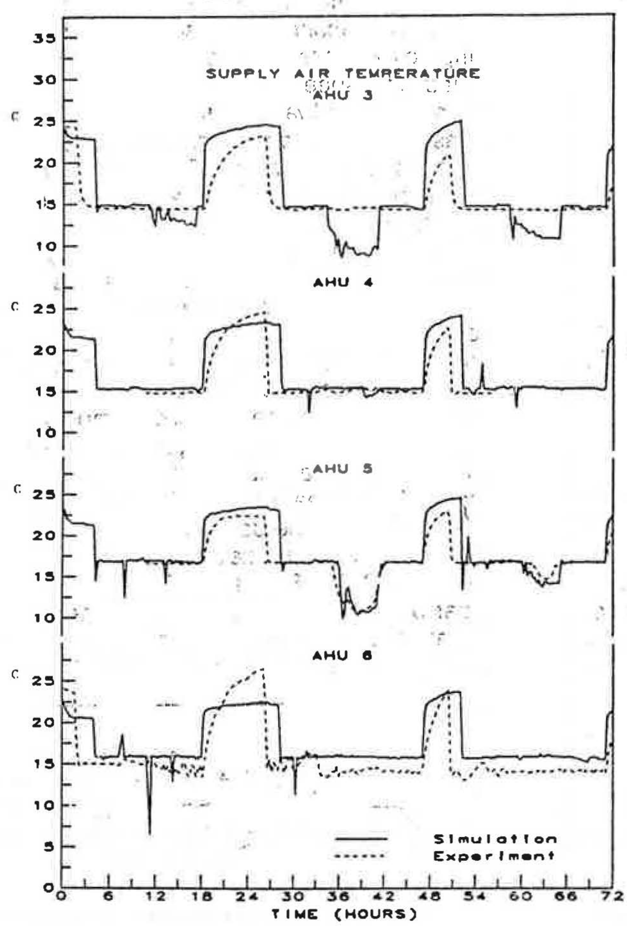

Figure 11 *Supply air temperatures of four air-handling units*

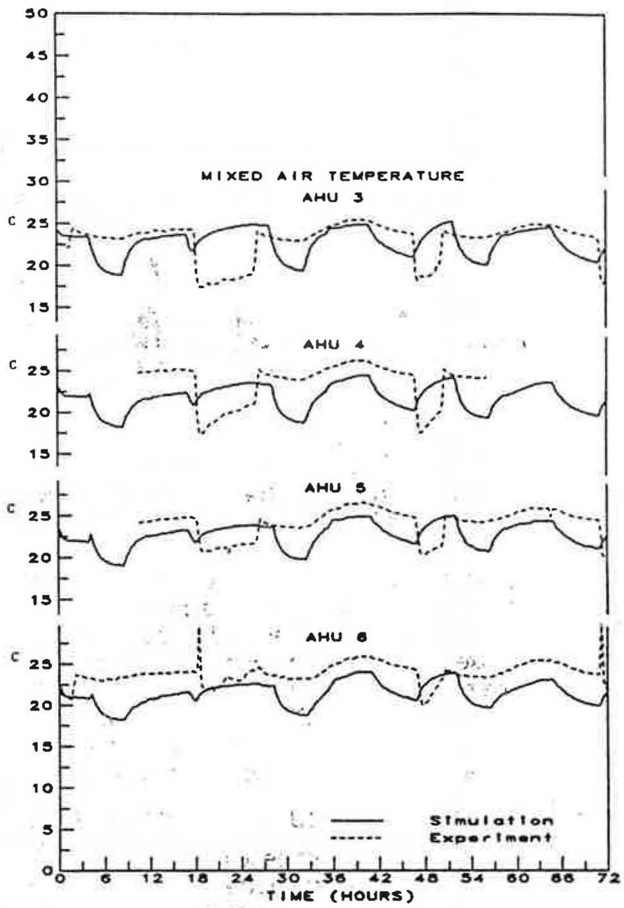

Figure 12 *Mixed air temperatures of four air-handling units*

and less than 14.5°C (58.1°F), a linear variation of the damper opening was made with respect to the outdoor air temperature.

A series of simulations was performed in order to compare the simulation results with the experimental measurements. Because many of the input values to the simulation model had to be estimated, repeated simulations with different input values were necessary until reasonable agreement between the simulations and experiments was achieved. The air temperatures from the simulations and experiments for AHU 3 and Zone 3 are compared to each other in Figure 10. The solid and dashed lines represent the simulation results and the experimental measurements, respectively. Occasionally, unreasonably high or low values (spikes) were present in the simulation outputs and were probably due to poor convergence of the equation solver. Those bad output data points were removed. The supply, mixed, and return air temperatures are denoted T_{50}, T_{46}, and T_{55} in Figure 4, respectively. The zone air temperature is denoted as T_{39} in Figure 5. Figures 11 through 14 present the supply, mixed, return, and zone air temperatures of all four units and zones. These figures show that reasonably good agreement between the simulations and experiments can be found.

Figure 15 shows some of the computed inner surface temperatures of Zone 3 with time. It should be noted that both inner and outer surface temperatures of the ceiling or the floor were assumed to be the same (i.e., treated as massive internal walls).

The supply air setpoint temperature in responding to the zone demand is shown in Figure 16. The high setpoint of 43°C was used to close the valve. Figure 17 depicts the power consumption by the cooling coil of AHU 3 with the supply air setpoint variation represented in Figure 16. As expected, peak power consumption occurred on the second day (September 23) when the solar heating load and the outside air temperature were highest during the three-day period (see Figure 8). During this simulation, the outside air dampers were closed and no nighttime purging was employed.

Start/Stop Control and Continuous Operation

Comparison of the energy consumptions resulting from the use of two control schemes—start/stop control and continuous operation—was made with the simulation model used for verification. A representative day of each month was selected for the cooling season (March to October) by abbreviating the yearly weather data of the Washington, DC, area from the "Weather Year for Energy

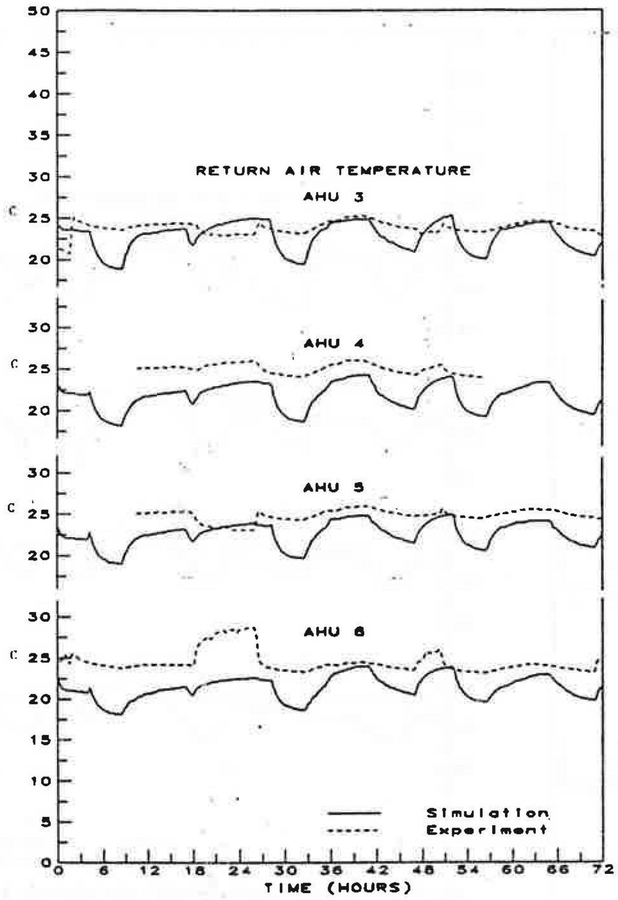

Figure 13 *Return air temperatures of four air-handling units*

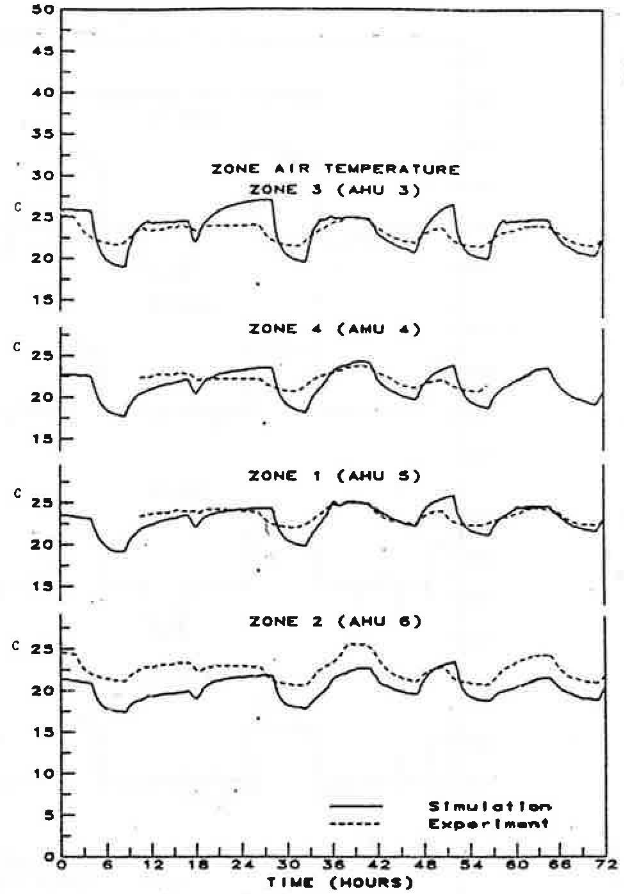

Figure 14 *Zone air temperatures of four zones*

Calculation (WYEC)" tape. For the abbreviation of weather data, the methodology of Nall et al. (1981) was used.

Figure 18 shows the energy consumptions of the cooling coils and fans for all four air-handling units under two control schemes. Under the continuous operation scheme, the cooling coils and fans operated all day. Under the start/stop control scheme, the operation of the cooling coils and fans began at 6:00 a.m. and ceased at 6:00 p.m. for all months of interest. The monthly energy usage shown in this figure was computed by multiplying the daily use by the number of working days of each month. Since the number of working days per month varied, the averaged value of 21.5 days was chosen for all months of the cooling season. It is obvious from this figure that the continuous operation of the air-handling units consumed much more energy than start/stop operation.

Nighttime Purging

The effect of nighttime purging on energy use was also investigated. The verified model was used along with the abbreviated weather data for the Washington, DC, area. Nighttime purging was scheduled in the simulations to be started at 1:00 a.m. and stopped at 6:00 a.m. During this purging cycle the outside air dampers were fully open, fans operated at full speed, and the cooling coil valves were closed.

Energy consumption by the cooling coils and fans for the two control modes, with and without purging, is compared in Figure 19. The start and stop times for operation of the cooling coil are 6:00 a.m. and 6:00 p.m., respectively. One can see that cooling coil energy can be saved during the spring and fall seasons with the purging cycle. But the electrical energy use by the fans offsets the savings and results in more energy consumption than without purging. Thus, the use of nighttime purging on the HVAC system of the NIST administration building would not be beneficial in saving energy and would, in fact, result in increased operating costs.

Figure 20 depicts the cooling coil power consumption of air-handling unit 3 (AHU 3) in the month of May. Figure 21 shows the cooling coil and fan energy use for the three different control schemes. From this figure, it can be seen that of the three control strategies investigated the current control scheme implemented by the NIST, which is the start/stop control without purging, is the most cost-effective control strategy.

CONCLUSION

The HVACSIM + program was found to be capable of simulating a large office building system with its many building shell, HVAC system, and control components. The estimation of the constant parameter values in the various

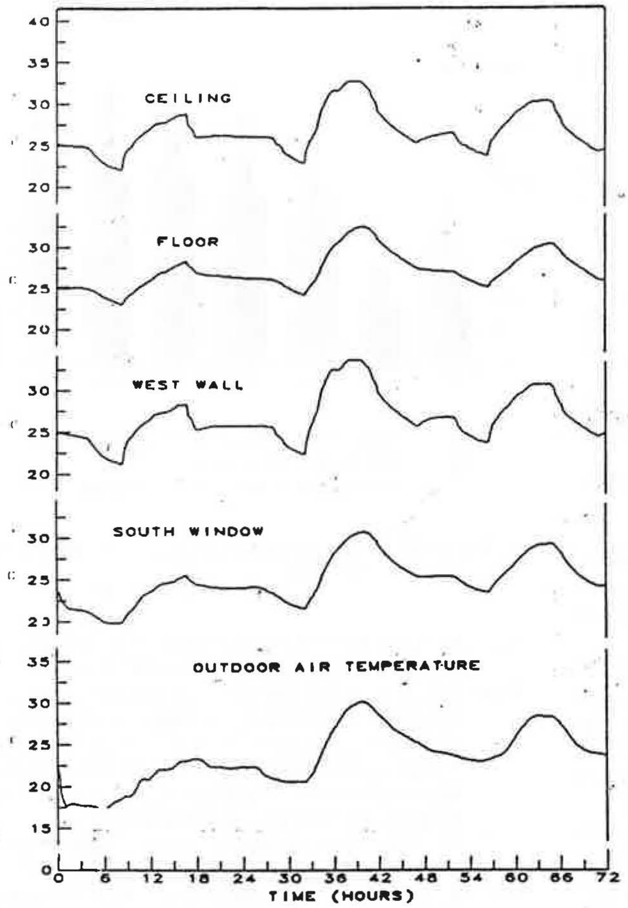

Figure 15 *Inner surface temperatures of constructs in Zone 3*

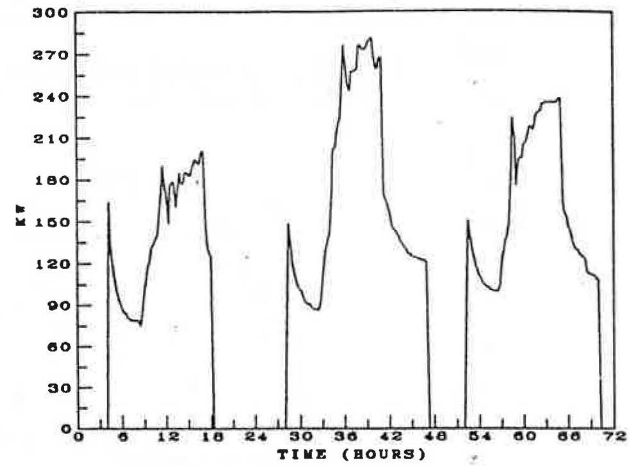

Figure 17 *The power consumption by the cooling coil of AHU 3*

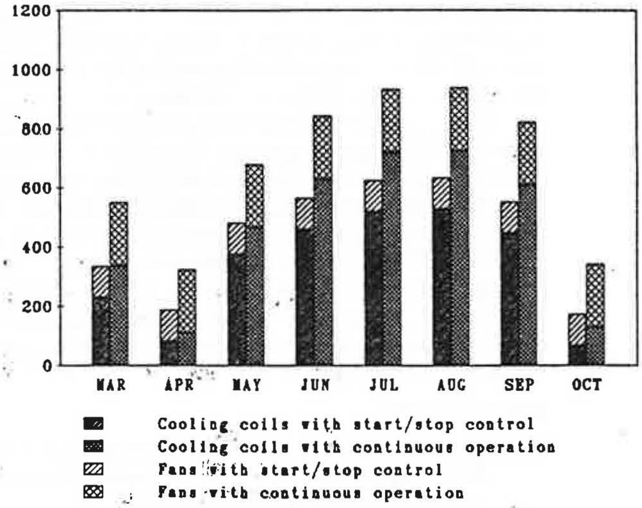

Figure 18 *The energy consumption by the cooling coils and fans of all four air-handling units*

component models and the assignment of initial conditions of state variables in the simulation greatly influenced the convergence of solutions. When step changes of state variables, especially boundary variables, were considerably large, some difficulties were encountered in obtaining reasonable solutions. Large error tolerances could

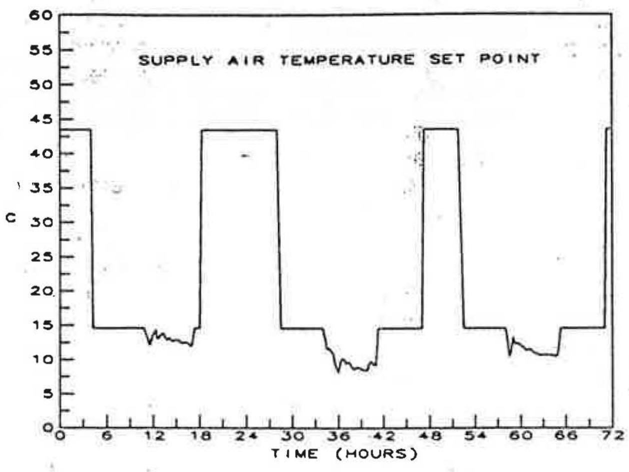

Figure 16 *The setpoint variation of the supply air temperature of AHU 3*

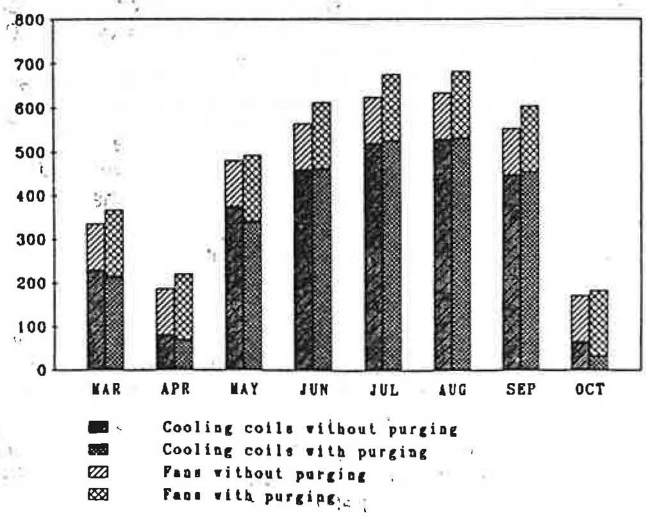

Figure 19 *Comparison of energy consumption with and without purging cycle*

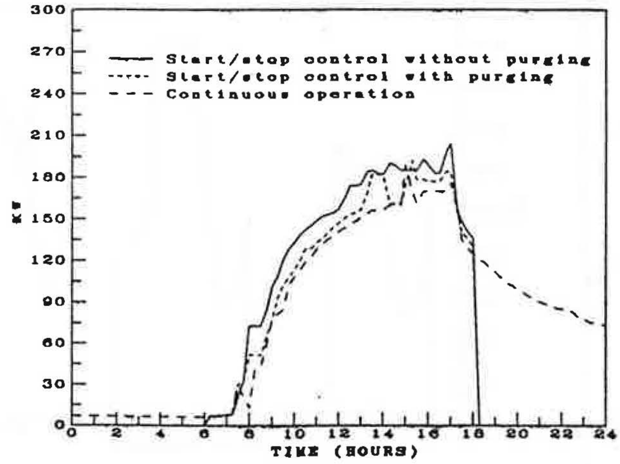

Figure 20 The cooling coil power consumption of AHU 3 in May

expedite a simulation computation, but the simulation result might then be incorrect. It was learned, through a series of simulation runs, that the most difficult task was the preparation of input data for a simulation.

The study of three different building control strategies showed that the use of a purging cycle in conjunction with the start/stop control strategy might not save energy. The simulation results of the NIST administration building showed that the start/stop control scheme without purging is the most cost-effective for the Washington, DC, area. Further energy savings might be realized if a computerized optimum start/stop control algorithm was implemented instead of the manual start/stop control currently used, but this was not investigated.

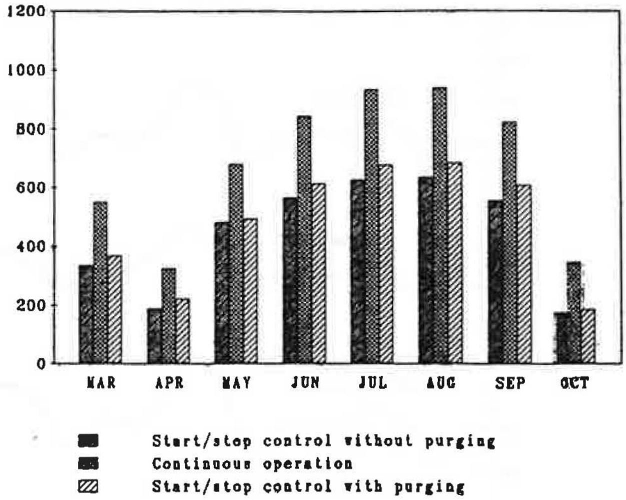

Figure 21 Summary of energy use of three different control schemes

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