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SPACE-HEATING CONSERVATION IN LARGE ACADEMIC INSTITUTIONS

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ABSTRACT

This paper describes the steps taken in energy conservation in the space-heating system of the State University of New York at Stony Brook. A model for the heating-ventilating and air conditioning system was developed. An experiment, which determined the dynamic behavior of one of the buildings was used to select the parameters of the model. The analysis of the model shows that between 60 and 70% of the total energy used in the space heating of the academic buildings is consumed in the ventilation systems of the campus. Studies of the steam generation plant shows that "normal" operation of the system is very inefficient and that significant savings in energy can be achieved, without capital investment, simply by planning the way in which the energy is consumed. Finally, the areas where this type of analysis may be applied to other institutions of comparable size and complexity are discussed.

Introduction

The prospects of reduced fuel-oil allocation as well as the rapid increase in its price has caused universities, as well as business and industry, to look closely at the operation of their heating, ventilation and air conditioning (HVAC) systems. Analysis of the systems at Stony Brook show that substantial savings can be achieved without major disruptions in the academic activities, and without capital investment.

In order to understand the workings of the system, a simulation model was created to predict the dynamic behavior of the buildings. The campus has eighteen major academic buildings, all of which have the same general type of construction: poured concrete and brick outer walls, poured concrete floors, and glass and steel windows. In addition, the space usage falls into three categories: office, laboratory and classroom space. The ventilation systems are natural

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convection in some portions of the older buildings and forced air in the new buildings. The major differences in the architecture is in the number and size of the windows. The parameters of the model were determined by performing an experiment on one of the office buildings while it was unoccupied. The parameters for the rest of the buildings were simply scaled from those chosen for the building studied in detail.

The power plant consists of three 60,000 lb. Bigelow and one 60,000 lb. Cleverbrook boilers. The power plant was designed to supply steam to academic building and dormitories at building design conditions: 0°F and 15 mph wind. A large fraction of the steam lines are old and leaky and the boilers themselves are reaching the end of their useful service.

While it is impossible to generalize the detailed results from the Stony Brook campus to other universities and industrial research centers, the conclusions drawn probably do indicate the areas of major concern for others. In addition, this study shows that large quantities of fuel-oil can be saved by the detailed analysis of the workings of the HVAC systems even without any changes being made in the physical plant itself.

Temperature Dynamics Model

Figure 1 is the floor plan of an arbitrary space to be heated or cooled. In the model the following notation is used

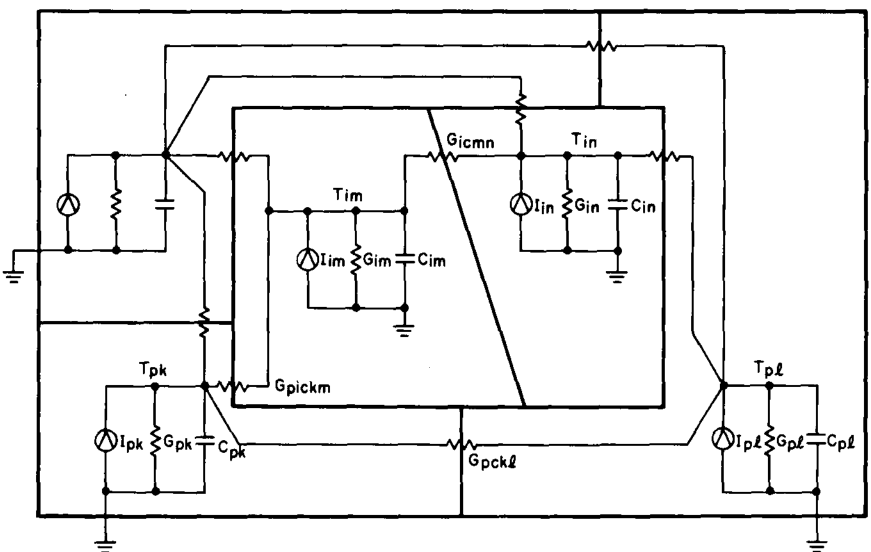

Figure 1. Model for arbitrary building plan. Heat conduction through the walls and floors between rooms is represented by a conductance. The "ground" symbol represents heat conductance to the outside of the building through the windows, doors, walls, and ceiling.

I_{pk} = perimeter heat source

G_{pk} = heat conductance through the perimeter for the k^{th} space.

$G_{pck\ell}$ = heat conductance between perimeter rooms k and ℓ.

C_{pk} = heat capacitance for the perimeter space k.

T_{pk} = temperature of the k^{th} perimeter space.

I_{im}, G_{im}, C_{im}, G_{icmn}, T_{im} have the same definition except for the interior spaces.

G_{pickm} = heat conductance between perimeter room k and interior room m.

In steady state all of the T_p's and T_i's come to the same value (assuming the building to be properly balanced) hence the model reduces to the simple circuit shown in Figure 2. In the steady state model, the total heat current is given by

$$I = \sum_{k=1}^{n_p} I_{pk} + \sum_{m=1}^{n_i} I_{im} \tag{1}$$

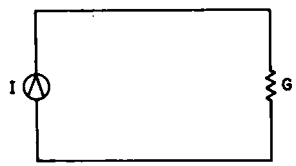

Figure 2. The steady state model of a balanced (i.e., $T_{pk} = T_{im}$) building.

and the total heat conductance is given by

$$G = \sum_{k=1}^{n_p} G_{pk} + \sum_{m=1}^{n_i} G_{im} \tag{2}$$

in Equations (1) and (2) n_p and n_i the number of perimeter and interior spaces, respectively.

In a building without forced ventilation, the major heat loss will be through the windows and doors. Hence, the heat flow will be primarily "radial" (i.e. from the interior to the perimeter and from the perimeter to the outside of the building). With this assumption we may set

$$G_{pckm} = G_{icmn} = O \tag{3}$$

If it is further assumed that all interior spaces are adjacent to a perimeter space (i.e. heat from one interior space does not have to pass through another interior space to get the perimeter) the model reduces to that shown in Figure 3. The model illustrated in Figure 3 is, of course, overly simplified. The actual temperature variation will vary from one side of the building to the other. For

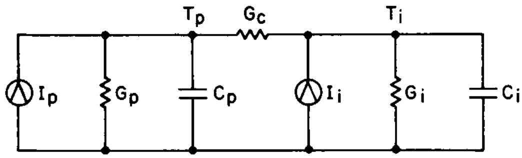

Figure 3. A simple dynamic model of the building.

example, the sun can cause the temperature of one side of the building to rise several degrees in a few hours, while the other side continues to cool. Such inbalances will cause heat flow which is "lateral." In actual experiments, however, while sun heating and wind cooling were observed, the dynamics of the building were such that Figure 3 represents a fairly good model for the average behavior of the building. The parameters in Figure 3 may be obtained from those in Figure 1 by the following equations:

$$G_p = \sum_{k=1}^{n_p} G_{pk}, \qquad C_p = \sum_{k=1}^{n_p} C_{pk}, \qquad I_p = \sum_{k=1}^{n_p} I_{pk}$$

$$G_i = \sum_{\ell=1}^{n_i} G_{i\ell}, \qquad C_i = \sum_{\ell=1}^{n_i} C_{i\ell}, \qquad I_i = \sum_{\ell=1}^{n_i} I_{i\ell} \tag{4}$$

$$G_c = \sum_{k>m}^{n_i, n_p} G_{pickm}$$

The model of Figure 3 will reduce to that in Figure 2 if $T_p = T_i$.

The physical significance of each of the parameters is easily understood. The heating systems of the buildings are those commonly used in large buildings. Under each window and beside each door is a perimeter heat source. The perimeter heat sources are designed to make-up for the heat lost through the doors and windows. The temperature of the rooms are maintained by a reheat coil which raises the temperature of the mixture of fresh air and the recirculated air (if any). The heat sources I_p represents the perimeter heating sources while that for the interior represents only the reheat-preheat sources. The conductance G_p is primarily due to the windows while G_i (which should be quite small) is primarily due to losses through the roof. The coupling conductance G_c represents the resistance to the flow of heat from the interior to the perimeter. The most common path for this later flow is through the interior walls and over the walls through the false ceiling. Clearly, the larger the number of coupled circuits retained in the model, the more accurately the simulation model will follow the behavior of the actual building, however, as is shown in next section, the model in Figure 3 is able to track the behavior of the building tested quite accurately.

The values of the parameters used in the circuit were obtained from a computer simulation which was able to track the actual behavior of the temperature in the building with $I_i = I_p = O$. The actual variation of the outside temperature was used to modulate the value of the parameters G_p, G_c and G_i. This is possible since, with the outside temperature constant, the temperature T_p or T_i is of the form

$$T_p = Ae^{-S_i t} + Be^{-S_2 t} \tag{5}$$

where A and B are proportional to ΔT (i.e. the difference between the inside and outside temperatures. Since S_1 and S_2 are very small, the exponentials can be expanded. The result, to first order, is that the temperature variation when the outside temperature is not constant is given by

$$T_p = A_O\,(1 - \frac{S_1 \Delta T}{\Delta T_O}\,t) + B_O\,(1 - \frac{S_2 \Delta T}{\Delta T_O}\,t) \tag{6}$$

where A_0, B_0 and ΔT_0 are chosen at an (arbitrary) temperature difference of 20°C. (i.e. $T_{p,i} = 68°F$, $T_0 = 32°F$).

The values of C_p and C_i were selected so that they would have the same ratio as that of the perimeter volume to the interior volume of the building. (In the case of the building tested $C_p/C_i = 7.5$).

In order to test the model and select the parameters, it was necessary to take data on at least one building. To cause as little disruption as possible, a building which is used exclusively for office work was selected (the Administration building). The construction of this building is similar to the other buildings and it has an average window area. The building has three stories above ground and has approximately 120,000 square feet of floor space. Approximately 75% of the air is recirculated and 25% fresh make-up air is brought in.

At 5:00 P.M., December 28, 1973, all heat delivered to the building was turned off and remained off for a total of 110 hours. The heat came on again at 7:00 A.M., January 2, 1974. The ventilating and circulating fans were turned off for the first 5 hours, turned on for the next 8 hours, and then turned off for the remainder of the experiment. During this period (110 hours) the average outdoor temperature was 39°F or 4°C. Apparatus capable of continuously recording the temperature was placed in a north side, third floor office suite. This recording station monitored the perimeter temperature and the temperature in the hall outside of the office suite. Another recording station was placed in a south side, 2nd floor office. This station monitored the interior office temperature and the outside temperature.

The following is a summary of the data gathered by these stations:

1. After 110 hours (approximately 4 and 1/2 days), the temperature in the 2nd floor interior office had only fallen to 68°F (a decrease of 8°F).

2. The lowest temperature recorded was 48°F in the north side, 3rd floor, perimeter office space (9°F above the average outdoor temperature for the period. Both outdoor temperature and wind velocity were obtained from a nearby weather station).
3. While the rate of temperature decrease did show correlation with the wind velocity, the dependence was very weak.
4. The cooling rate varied from 0.4°C/HR at the perimeter (with outside temperature of 0°C) to approximately one fourth that amount in the interior.
5. The sun produced substantial increases in the room temperature of the building. (The temperature of the interior office space on the south side increased nearly 2°C between 40 and 45 hours after the start of the experiment, i.e. between 9 A.M. and 2 P.M. December 30, 1973.)

In Figures 4 and 5 the data is displayed.

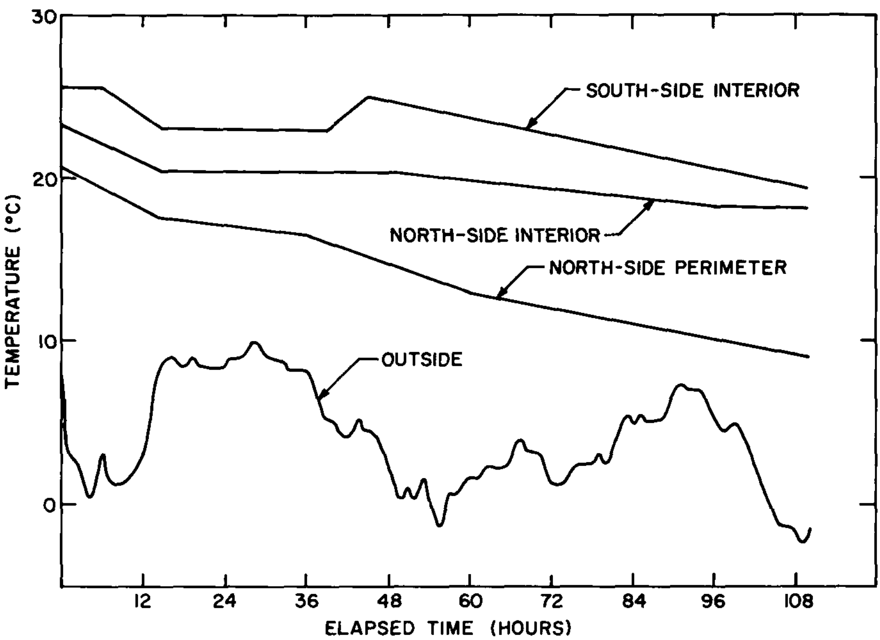

Figure 4. Temperature variation of the building as recorded at stations located in various parts of the Administration Building as well as the outside temperature. The ventilation fans were turned on after 5 hours and off, and remained off, after running for 8 hours. The rise in temperature in the south-side interior rooms was due to the bright sunlight on the afternoon of the second day of the experiment.

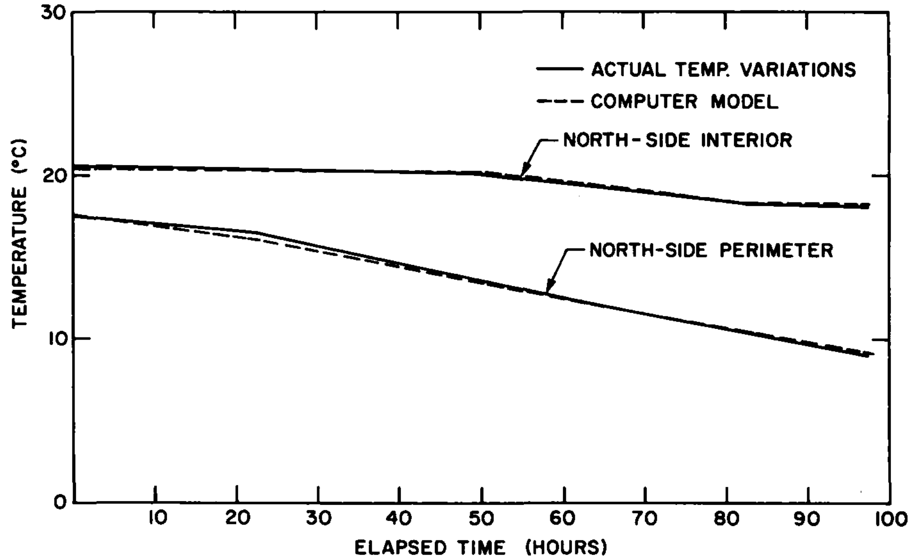

Figure 5. Comparison between the actual temperature variation and that produced by the computer model for the north-side interior and perimeter rooms. The starting time for the comparison is at the time of the shut down of the ventilation system.

Once the values of G_p, C_p, G_c, C_i and G_i were determined for the best fit to the data for the cooling of the building over approximately 100 hours, it is possible to determine the effect of the ventilation system. The ventilation fans were on, without reheat, for approximately 8 hours near the beginning of the experiments. From the cooling rate of the building and the outdoor temperature data it was possible to select a heat conductance G_v in parallel with G_p and G_i (with G_c set equal to zero due to the direct coupling of the interior to the perimeter through the forced air circulation system) which determined the rate of fall of temperature during this cycle.

Once the parameters are selected to simulate the cooling rates under the various conditions, the model can be used to predict steady state behavior. The following are the major conclusions obtained from the model:

1. The heat loss from the building is directly proportional to the temperature difference between the inside and outside temperatures. (There is a small change in the amount of heat loss caused by the wind. This change is quite small so long as the wind velocity is below 15 mph.)
2. The ventilating fans constitute between 65% and 75% of the total heat loss of the building tested.

In the short time available and without disrupting the academic and research activities of other sectors of the campus, it was impossible to test other buildings. Without an actual experiment being performed on all of the buildings on campus, it is of course impossible to accurately predict cooling dynamics of the buildings. However, we feel we can at least estimate the effects by simply scaling the model used to simulate the behavior of the single building tested (which is both architecturally and mechanically similar to the other academic buildings). The "rules of thumb" used in this scaling are as follows:

1. The perimeter heat conductance is directly proportional to the window and door area of the building.
2. The heat capacity of the various parts of the building are directly proportional to their volumes, and
3. The heat loss through the vent system is directly proportional to the quantity of air expelled.

These rules, of course, are only approximate since the type of construction varies somewhat from building to building. In addition, the window area is not uniformly distributed over the building (north side windows will loose heat more rapidly than south side, for example). As normal shutdowns of the buildings occur (for repair of equipment, for example), temperature behavior data should be taken, and the estimated model corrected. However, until such data exists, it is our feeling that the estimated model will give a fairly accurate estimate of the temperature behavior of a given building.

Using the estimate model for the entire campus, the following results are obtained:

1. The ventilation systems of the eighteen academic buildings constitutes at least 40% of the *total* heating (and cooling) requirements of the *entire* campus.
2. The estimated model probably underestimates the effect of vents since the smallest values of heat conductance were chosen which would produce a model which would simulate the building's behavior in the scaling of the parameters for the entire campus.

The quantity of energy used in the ventilation systems of the various buildings differed considerably as might be expected. The large, modern laboratory buildings, which use the largest quantities of energy, consume between 80 and 90% of their heating/cooling energy in the ventilation of the laboratories. The graduate chemistry building, for example, has approximately 300,000 square feet of floor space and expells approximately 400,000 cubic feet of air per minute.

The buildings do not have individual consumption gauges, hence it is impossible to check the predicted consumption with measured values. However, the mechanical design figures are available for each of the buildings. The heating system is designed for 0°F and 15 mph wind. Comparing the design figures for the academic buildings and the figures for the model of the same conditions reveal that the model predicts to within about ± 1% the fractional consumption of each building. That is, the model is used to calculate the fraction consumed by a given building of the total energy consumption of the entire campus. The same calculation was made from the design figures and the agreement between these two sets of percentages was to within approximately 1% of the total energy consumed by each building.

With the aid of the model it is possible to determine policy alternatives for fuel-oil savings. For example, if a 25% savings in the energy used is desired it could be achieved in three ways:

1. The average temperature of all academic buildings could be maintained at 62°F (i.e. 10°F below the levels of one year earlier).
2. The temperature of all buildings could be maintained at 68°F combined with a shut-down of all ventilation fans for an average of 8 hours per day (not all fans in a given building would need to be shut off for 8 hours, however. Some fraction of the fans could be left on continuously, if others were shut off for a longer period of time).
3. The entire campus could be shut down for two weeks during the coldest part of the winter (or hottest part of the summer).

The second of these three alternatives has the added advantage that substantial quantities of electricity would also be saved (approximately 10% the total campus usage). However, when we examined the way in which steam (high-temperature hot-water) was generated, we found that a saving in energy usage need not be translated into an equal amount of fuel oil saved.

Analysis of the Power Plant

The central conclusion of our year long study of the heating/cooling system at Stony Brook was that savings in energy usage can only be translated into corresponding reductions of fuel-oil consumption if there is sophisticated management of the heating plant. For example, if the heat load is cut during the evening hours by turning off ventilating fans in the sections of the academic buildings which are not being used for research (or special purpose equipment such as computer or animal ventilation) the efficiency of the steam generation may decline so much as to nearly cancel the drop in load. Only with a planned anticipation of the load change can the operational efficiency be held constant. Until this year, almost no data on daily fuel consumption was taken. The metering of the heating plant is still inadequate to be able to measure hourly efficiency of a given boiler.

The heating plant was designed so as to be able to meet a peak demand: those corresponding to the 0°F and a 15 mph wind conditions. However, such extreme weather conditions are rarely encountered on Long Island. During the past two years there were no 65 degree day weather conditions during the winters. Yet, the power plant is designed to meet these conditions and the only gauge for the operations is that the required steam pressure be met.

While data on monthly oil consumption was available from delivery information for the past years, no daily consumption data was available. In addition it was impossible to tell how much oil was consumed by an individual boiler (hence, the individual boiler efficiencies were unknown). Starting in January of 1974 we were able to begin the daily gathering of consumption data on individual boilers. Even with this paucity of data, by the end of February two central conclusions were obvious:

1. Fuel-oil consumption was much less efficient on the warmer days and
2. Fuel-oil consumption during the past winter was more efficient than the previous one because the required load the plant had to meet had been increased.

The quantity of fuel-oil consumed should be proportioned to the number of degree days (d.d.) neglecting the effect of wind. The data fits the line $Q = md + b$, where Q is the quantity of fuel oil consumed, d the number of degree days, m the slope and b the intercept, with a correlation coefficient [1] of 0.73. However, considering the warmer days alone (i.e., d.d. $\leqslant$ 15) gave a much smaller slope and higher intercept than when the colder days were considered alone. One of the problems is that the d.d. represents a long term average of the weather conditions. For example, one 24 hour period of warm weather can be followed by a 24 hour period of much colder weather. If the two periods fall in the periods corresponding to days, one will have a small d.d. while the other will have a large d.d. If on the other hand the periods fall between the days, the d.d. will be an average of the large and the small values of d.d. In order to partially overcome this difficulty, we made 2, 4 and 8 day averages of the single d.d. data. That is, the data for each 2 day period was obtained from the single day data by simply adding the d.d. and the consumption for each pair. In a similar way the data for the 4 and 8 day averages was obtained. This way of handling the daily data gave a better agreement between the daily consumption data and the monthly delivery data. The average daily data gave a consumption of $Q \cong 800$ Gal/dd + 6,000 Gal. while the delivery data gave $Q \cong 750$ Gal./d.d. + 7,500 Gal. Using the single day data alone gave $Q \cong 450$ Gal./d.d. + 14,000 Gal. These results suggest that the operation of the plant was very inefficient on warm days. Further support for this notion was obtained when the consumption of the last two winters was compared.

Between the winters of 1972-73 and 1973-74, three new buildings were opened. In 1972-73 there were 3.826 million square feet of academic buildings and dormitories heated by the power plant. In 1973-74 nearly one million square feet was added (bringing the total to 4.824 million square feet). During these two periods the heating plant remained almost completely unchanged, yet there was almost no change in the amount of fuel oil consumed! For 1972-73 the delivery date showed daily consumption to have been Q = 700 Gal./ d.d. + 8,000 Gal. In terms of fuel-oil consumption per square foot of building space heated, 1973-74 required nearly 45% less to heat than 1972-73! A detailed look at the daily consumption per boiler shows why this should be true.

On cold days (d.d. > 45) nearly all of the boiler capacity was needed to maintain the proper steam pressure. However, after a week or so of cold weather, there were periods of warmer weather, yet all of the boilers were still used, each consuming a few thousand gallons of oil per day, producing a total consumption far in excess of what was necessary. If a single boiler had been used, consuming the same quantity of oil it had consumed during the cold period, the steam could have been delivered with far less fuel oil consumption.

After this pattern was discerned, it was recommended that the plant operations at least try to meet the demand for steam by using a single boiler on those days which were forecast to be mild. On a few days during this spring, the total demand was met with a single boiler. On other mild days the demand was met with as many as four boilers. (The use of a large number of boilers usually followed periods of severe weather when all or most of the boilers were needed to meet demand.)

The data for the spring months (April and May) was grouped according to the number of boilers to meet the demand. The results indicate a clear trend.

1. Days when one boiler was used
   Q = 9,900 Gal. + 360 Gal./degree days.
2. Days when two boilers were used
   Q = 11,100 Gal. + 75 Gal./degree days
3. Days when three boilers were used
   Q = 18,400 Gal. - 170 Gal./degree days.

The negative sign for the three-boiler-use days shows that the reduction of the load will cause the boilers to operate even more inefficiently and actually require more fuel. Up to about 6 degree day weather, a single boiler is more efficient than two and up to about 20 degree days two boilers are more efficient than three. No attempt was made to determine which of the boilers would be most appropriate of the five boilers to use on mild days, however, a modest expense for steam gauges could produce substantial savings in fuel-oil through the selection of the best combination of boilers to be used under various weather conditions.

A strategy should be developed to meet the various weather conditions. While there are daily weather variations, most changes take place over a period of a few days (the time taken for a high pressure zone to pass over the region). Knowing the lag time in the temperature of the building to be of the order of a day or more, a strategy in which a five-day weather forecast can be used to plan the combination of boilers to be used over the period. Once the strategy is implemented, it should be stuck to with the confidence that the temperature of the buildings will remain nearly at the desired level even if the forecast proves off by a few per cent. In order to implement such a plan both start-up and steady state efficiencies are needed for each boiler.

Conclusion

The experimentation and analysis described in this paper are, of course, strictly applicable to a single institution. However, several conclusions have wide (if not general) application.

1. Energy conservation measures for space heating must consider the entire system—both uses and generation. In this particular case, it is shown that there are a number of ways of achieving *potential* energy savings by reduction of temperature and shuting off ventilation systems, however, if the shedding of a load is not coordinated with, and planned for by the steam generation plant, there could be an actual increase in energy use under some conditions.
2. While the actual fraction of the load produced by the ventilating system will vary from building to building, this study emphasizes the importance of the air-handling system in the planning of energy conservation measures. One of the quickest ways of determining the dynamics of a building is to construct a simulation model from the data obtained from actual experiments. Once the model is verified, various heating/cooling strategies may be tested on the model, and more accurate predictions of the potential savings can be made.

In past years it seems to have been assumed that no matter how a power plant was run, the cost of improving the operation was not justified. This past year's increase in fuel-oil prices has completely outdated such assumptions. From the analysis of the Stony Brook system, it is clear that the careful management of this type of facility can easily save the salary of the manager without any additional capital outlay.

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