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TERMINAL REGULATED AIR VOLUME (TRAV) SYSTEMS

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ABSTRACT

Variable-air-volume (VAV) systems can operate much more efficiently by integrating the control of the central fan with terminal controls. In such a scheme, supply air static pressure is reduced whenever areas of the building are not experiencing peak design conditions. Computer simulations (Hartman 1989; Englander 1990) based on typical office VAV applications have shown that as much as 50% of the fan energy required for VAV systems is saved by what is now called a terminal regulated air volume (TRAV) control strategy.

In applying TRA Vto buildings, a number of other new opportunities to further enhance the energy efficiency and improve the comfort/air quality conditions have also been developed. New HVAC control ideas that were developed for TRAV that have been successfully integrated into recent TRAV designs include:

1. *Continuous (24-hour) operation of the HVAC system, including running the fan at low speed during the night to distribute warm core air to the perimeter during cold weather and purge the building with cool outside air in warm weather, resulting in substantial additional energy savings and improved comfort/air quality.*
2. *Integrated lighting and HVAC control to operate the lights for each office or zone and at the same time automatically establish occupancy conditions for the HVAC system in order to concentrate temperature control and outside air ventilation efforts on the occupied zones.*
3. *Multiple space temperature sensors to control each VAV box when rhat box serves more than a single office or area.*
4. *Terminal VAV box airflow control by nonlinear strategies that offer improved comfort control throughout the building.*

This paper discusses these design components of early TRAV systems. The actual peformance of the above features is reviewed, and conclusions about incorporating these features in future direct digital control (DDC) applications for typical buildings are presented.

INTRODUCTION

Terminal regulated air volume (TRAV) is an HVAC and lighting control strategy that has been made possible with the introduction of high- performance full-DDC systems. TRAV systems have successfully utilized new capabilities of the emerging high-performance DDC systems. The results of the early TRAV applications point a path to designing buildings that are more comfortable, enjoy higher indoor air quality, and at the same time operate with unprecedented low energy requirements. The innovation that led to the development of TRAV is a more efficient method of VAV fan flow regulation. However, TRAV system concepts include a number of other design innovations that offer outstanding opportunities on their own to improve the energy and comfort performance of buildings. The purpose of this paper is to describe the elements of recent TRAV designs and discuss the effectiveness of these elements.

WHAT IS TRAV?

In a terminal regulated air volume (TRAV) system, the central fan is regulated to meet terminal VAV box airflow requirements rather than a duct static pressure setpoint. Under the TRAV control strategy, supply air is provided at reduced duct static pressures whenever possible. When areas of the building are not experiencing design loads, significant static pressure reductions occur in TRAV systems. Figure 1 shows the fan.power required at various airflows for TRAV control and several standard VAV control strategies. Experience from the early TRAV designs have illustrated that Figure 1 is a reasonably accurate representation of fan power requirements under the listed fan control alternatives.

However, TRAV designs incorporate much more than a fan power reduction strategy. Extending a high-performance DDC system throughout the building down to the terminal VAV boxes offers the use of advanced logic to reach unprecedented low energy use and, at the same time, achieve much improved levels of comfort and environmental quality. To accomplish these ambitious goals, TRAV system designs have employed advanced DDC system

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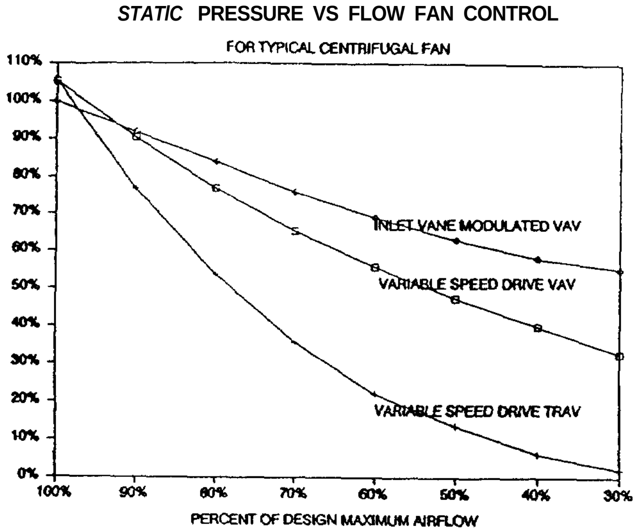

Figure 1 *Variable-speed fan performance comparison.*

capabilities to provide the following significant innovations to HVAC design in addition to terminal regulation of the fan:

Continuous HVAC Operation

Traditional thinking concerning energy conservation in buildings has focused on keeping the HVAC system off when the building is unoccupied. Unfortunately, this strategy compromises the comfort and air quality of those who increasingly wish to work in buildings beyond regular working hours. In today's commercial and institutional buildings, the concept of building shutdownis rapidly losing its attractiveness because of the occupants' demands for occupancy flexibility and better comfort and air quality. This trend is well known to building operators. A trend that is not so well understood is that building shutdown is also rapidly becoming obsolete by more efficient building envelopes.

In old, poorly insulated buildings, turning HVAC systems off was about all the operator could do to reduce energy use. But the development of more effective building envelopes is changing the pattern of energy use in buildings. Today's buildings have a much higher ratio of building mass' to envelope loss than older buildings. This trend has made the thermal inertia of buildings a significant component in mechanical system sizing and building operation. At the same time, the development of more efficient envelopes has decreased the impact of heat flows through the envelope on overall building energy use. For many buildings it can be more economical to maintain indoor comfort conditions than to shut the building down when sparsely occupied. Less setback lowers the heating and cooling peak requirements for building startup and permits energy exchanges within the building or with other systems at significantly higher heat transfer efficiencies.

The key to achieving energy reductions with 24 hour operation is to develop an efficient building envelope system and high part-load efficiencies for the HVAC energy conversion systems. Figure 1 illustrates how little power is required by a terminal regulated fan at low flows. In the TRAV system concept, the air system is used during low occupancy hours to maintain building pressurization in order to control infiltration and to purge the building with cool night air during anticipated warm weather or transfer the heat in the building core to the perimeter areas in cold weather. These transfers are accomplished at about 25% of design airflow, which requires less than 2% of the design fan power. To obtain fan efficiencies at very low flows and static pressures requires variable-frequency-drive (VFD) airflow control with good operating efficiencies (at least 95% or better) at all speeds.

Continuous operation strategies also permit the downsizing of equipment (von Thun and Witte 1991). By eliminating the need for building startup each day and by adopting control strategies that utilize the thermal inertia of the building, the first two TRAV projects provided observed peak cooling reductions of approximately 30% and 50 % , respectively.

Finally, the continuous operation strategy has an enormously positive impact on comfort and air quality in buildings during normal work hours, and especially during the off hours building occupants increasingly wish to work. Because of the very low fan power required to supply low air volumes, TRAV systems are well suited to provide 24-hour seven-day-a-week HVAC operation.

Integrated HVAC and Lighting Control

In the past, building controls have required that the building operator or mechanic establish an occupied hour schedule for the building. Lighting control (if present at all) was usually accomplished with simple time sweeps in a low-voltage lighting system. In TRAV designs, the DDC system is connected to each terminal VAV box where it can easily be extended to include lighting control. Lighting/HVAC control integration offers excellent opportunities through synergism to improve the performance and efficiencies of both the HVAC and lighting systems. The expanded logic capabilities of DDC systems can offer lighting control schemes that are more effective in accommodating occupant needs, yet result in fewer lighting operating hours than simple sweep strategies. Furthermore, monitoring occupancy on a zone-by-zone basis provides an opportunity for additional improved comfort and energy savings by allowing the HVAC system to direct its efforts toward those areas of the building that are actually occupied.

The most obvious synergistic benefit of combining lighting and HVAC control is that the lights indicate the occupancy status of each zone. Other benefits stem from the fact that modem buildings are rarely 100% occupied. By establishing office-by-office occupancy conditions, it is far easier to provide comfort to the actual occupants during peak weather conditions, which is a time when many offices are vacant.

Distributed DDC control of lights can also be more effective than traditional lighting control strategies. Most lighting control schemes use centralized lighting panels with “lighting sweeps” that turn off all lights at specified time intervals. Under TRAV operation, the lighting zones are typically much smaller (a single enclosed office is one zone), and the lighting control relays are located at each zone. Lighting sweeps are absent. Instead each zone’s lights operate individually. Under pushbuttoncontrol, the pushbutton acts as a toggle, turning the lights and occupancy status “on” if presently off, or "off" if presently on. In addition, during unoccupied hours, the lights will automatically shut off after a period of time if the occupant does not shut them off. With occupancy sensors, logic between the occupancy sensor input and lighting output is employed to ensure efficient lighting operation without some of the nuisances associated with standard occupancy sensor control.

There are several methods that can be employed to determine occupancy on a zone-by-zone basis. The most effective is the use of occupancy sensors. Occupancy sensor technology has advanced rapidly in the last few years. The performance of these devices has improved substantially, while the manufacturing costs have continued to decrease. The two major detection methods, infrared and ultrasonic, are both very effective in detecting occupancy in the workplace. The combination of advanced DDC system logic capabilities and occupancy sensor improvements means that fewer sensors may be adequate to monitor open office applications. However, it is very important that occupancy sensing designs be conservatively developed, because even small difficulties can result in very negative responses from occupants.

The most common and economical occupancy sensing method is a low voltage pushbutton similar to those employed in low-voltage lighting systems. The pushbutton may be integral with each space temperature sensor, it may be located separately, or it may be a combination of both. When the occupant arrives and pushes the button, the DDC system is alerted to the occupied condition. The lights in the area are turned on, and the HVAC terminal unit(s) that serves the office or area is switched to the occupied mode, ensuring outside ventilation air will be delivered to the zone and space temperature will be controlled within tighter limits. The logic of the DDC system determines how long the space will assume occupancy, and depends on time of day and whether it is a weekday, weekend, or holiday. Normally, pressing the occupancy button when the lights are already on alerts the system that the occupant is leaving. The lights will shut off and the HVAC system will revert to the unoccupied control state until the pushbutton is pressed again. Generally, at the conclusion of the occupancy period, a short flash of the lights tells the occupant it is necessary to press the button to restart the occupied mode. Otherwise, the lights shut off after several minutes and the HVAC system reverts to the unoccupied mode.

Multiple-Space Temperature Sensors Controlling Each VAV Box

TRAV designs have developed a one-to-one congruence of lighting zones with HVAC zones, and a single terminal unit (VAV box) may serve more than one zone as shown in Figure 2. In all TRAV designs, an occupancy input device (a pushbutton, occupancy sensor, or both) provides an input to the DDC system that establishes the occupancy condition for the HVAC system and also turns on the lights. A comfort benefit of this approach is that temperature sensors

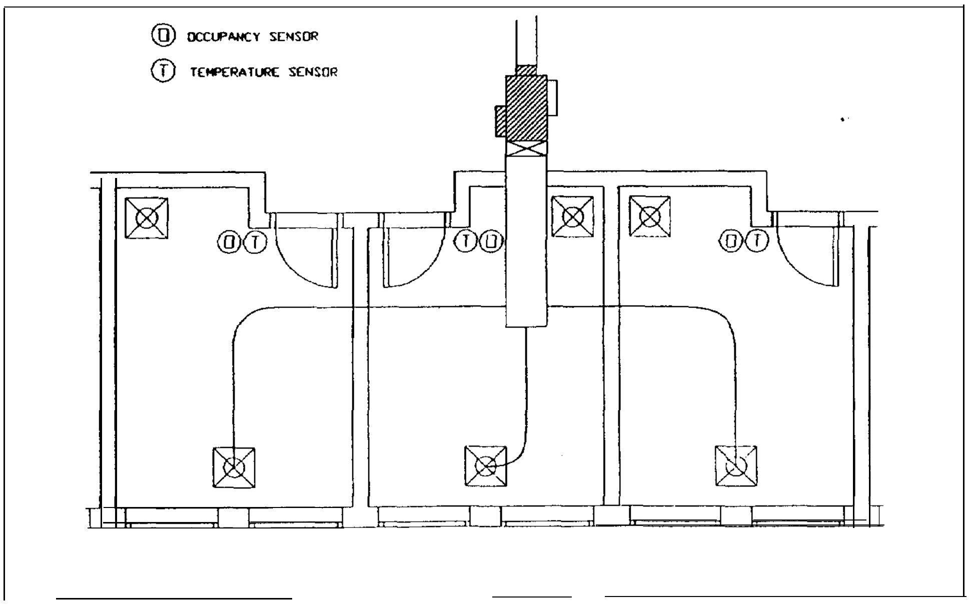

Figure 2

are placed with occupancy sensors in every zone. The use of multiple-space temperature sensors where VAV boxes serve more than a single office is very helpful in improving comfort conditions. Under TRAV operation during occupied hours, the temperature used to control the box is the average of the space temperatures of the occupied zones. However if any of the occupied zones are beyond the bounds of the heating or cooling setpoint, the weight of temperature in such space(s) is increased in the averaging calculation. Figure 3 shows the logic employed by TRAV systems to implement this simple but very successful averaging strategy.

VAV Box Airflow Control

Until recently, nearly all VAV box control strategies employed a proportional relationship between space temperature and airflow, limited by a box minimum airflow and a

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DOEVERY 1 M
      IF LIGHT_1 = ON THEN BEGIN
            IF ST1 BETWEEN HTGSPA CLGSPA THEN BEGIN
                  A2 = ST1
                  B2 = 1
            END
            ELSE BEGIN
                  A2 = ST1 * 2
                  B2 = 2
            END
      ELSE BEGIN :
            A2=0
            B2 = 0
      END

      IF LIGHT-2 = ON THEN BEGIN
            IF ST2 BETWEEN HTGSPA CLGSPA THEN BEGIN
                  A2 = A2 + ST2
                  B2 = B2 + 1
            END
            ELSE BEGIN
                  A2=A2+ST2*2
                  B2 = B2 + 2
            END
      END

      IF LIGHT-3 = ON THEN BEGIN
            IF ST3 BETWEEN HTGSPA CLGSPA THEN BEGIN
                  A2 = A2 + ST3
                  B2 = B2 + 1
            END
            ELSE BEGIN
                  A2 = A2 +ST3*2
                  B2 = B2 + 2
            END
      END

      IF B2 > 0 THEN
            BOX_SPACE_TEMP = A2 /B2
      ELSE
            BOX_SPACE_TEMP = AVG(ST1 , ST2 , SJ3)
ENDDO
  ---------------------------------------------------------------------------------------
LIGHT_1, LIGHT_2, LIGHT_3 ARE THE STATUS OF THE LIGHTING OUTPUT RELAYS FOR EACH OF
THE BOX'S SUBZONES

HTGSPA, CLGSPA ARE THE CURRENT HEATING AND COOLING SETPOINTS

ST1, ST2, ST3 ARE THE VALUES OF THE SPACE TEMP SENSORS IN EACH SUBZONE

BOX_SPACE_TEMP IS THE WEIGHTED AVERAGE SPACE TEMPERATURE

A2, B2 ARE LOCAL PROGRAM VARIABLES
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Figure 3 Program for averaging multiple space temperature sensors.

box maximum airflow. This relationship is shown in Figure 4. VAV systems have been correctly criticized for their failure to guarantee minimum outside ventilation air at all times. Furthermore, experience with dynamic control (Hartman 1989) has demonstrated that including separate heating and cooling setpoints along with a weather-calculated airflow for the range between the two setpoints benefits both comfort and energy performance. The weather-based airflow calculation is active in the temperature range between the heating and cooling setpoints. In this range, the calculation limits the airflow to (or close to) the minimum ventilation airflow in cold weather in order to permit the space temperature to rise and use the building as a thermal storage medium. In warm weather, when the system is in economizer operation, the airflow calculation is high in this range in order to cool the building and delay the need for mechanical cooling.

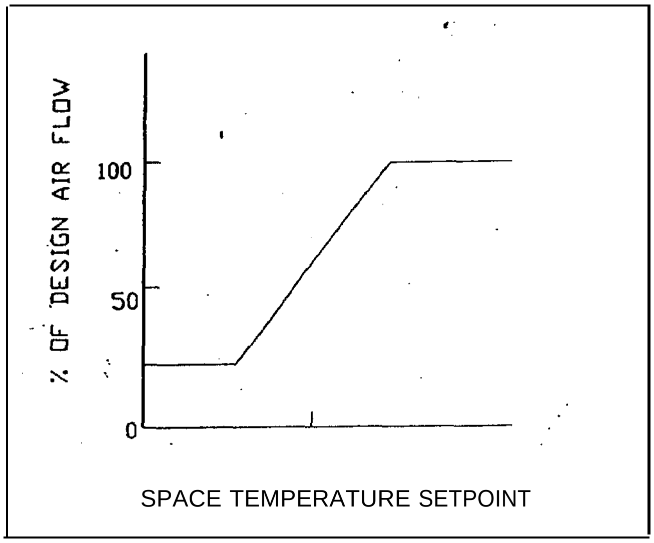

Figure 4

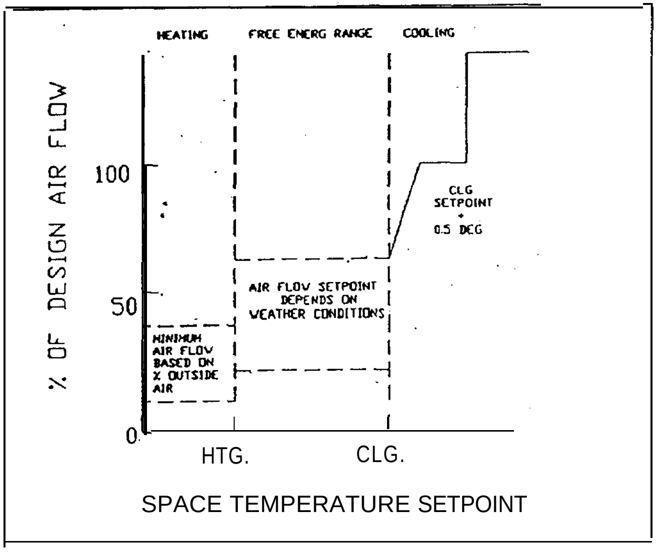

Figure 5

As TRAV strategies were developed, we also discovered that the use of the design maximum airflow for each VAV box can be much improved upon in many typical applications. In standard office applications, there is little reason to limit the airflow to this preset value if the space is well above temperature setpoint, especially when one considers each box to be a part of an integrated control system. As a result of simulation and field testing, the VAV box control scheme shown in Figure 5 was developed for TRAV operations.

In Figure 5 there is no fixed box minimum or maximum airflow. The minimum airflow at space temperatures below the beating setpoint is that which at the time provides the correct amount of outside air ventilation to the zone(s) served by box based on current occupancy conditions. The actual airflow is calculated from the current occupancy conditions (number of people in the zones served by the box) and the percent of outside air in the supply airstream.

Between the heating and cooling space temperature setpoints, the airflow setpoint for the box is based on the space temperature and the projected outside weather conditions. In warm weather, the airflow setpoint is high during economizer operation to maintain the space temperature at the lower end of the range in anticipation of warmer weather. In cold weather, the airflow setpoint is kept low in this range to allow the space temperature to rise to the upper end of the range in anticipation of heating requirements.

Above the cooling setpoint, the box airflow setpoint rises rapidly to the design cooling airflow, where it remains level for an approximately 0.3°F space temperature increase. At about 0.5°F above the cooling setpoint, the airflow setpoint is raised above the design maximum in order to provide all possible cooling and prevent a further space temperature increase.

This newly developed box control strategy has been very effective in providing required minimum ventilation air and maintaining more constant comfort conditions. In most of the early TRAV installations, occupants have noticed significant comfort improvements that appear to stem at least in part from this improved box control strategy.

DDC SYSTEM REQUIREMENTS

The HVAC design options listed above can offer economic and comfort/air quality benefits whether they are included as part of an overall TRAV system or applied individually, depending on the specific application. Because each of these items is largely is based on control improvements, they are ideal retrofit strategies. A building control retrofit presents an excellent opportunity to implement a complete TRAV system that includes all these features or any number of the applicable features alone. The case study presented in this paper is a retrofit of an existing mechanical system that includes all of the above-listed features.

DDC control system selection is a crucial element in the success of implementing these new control features. A

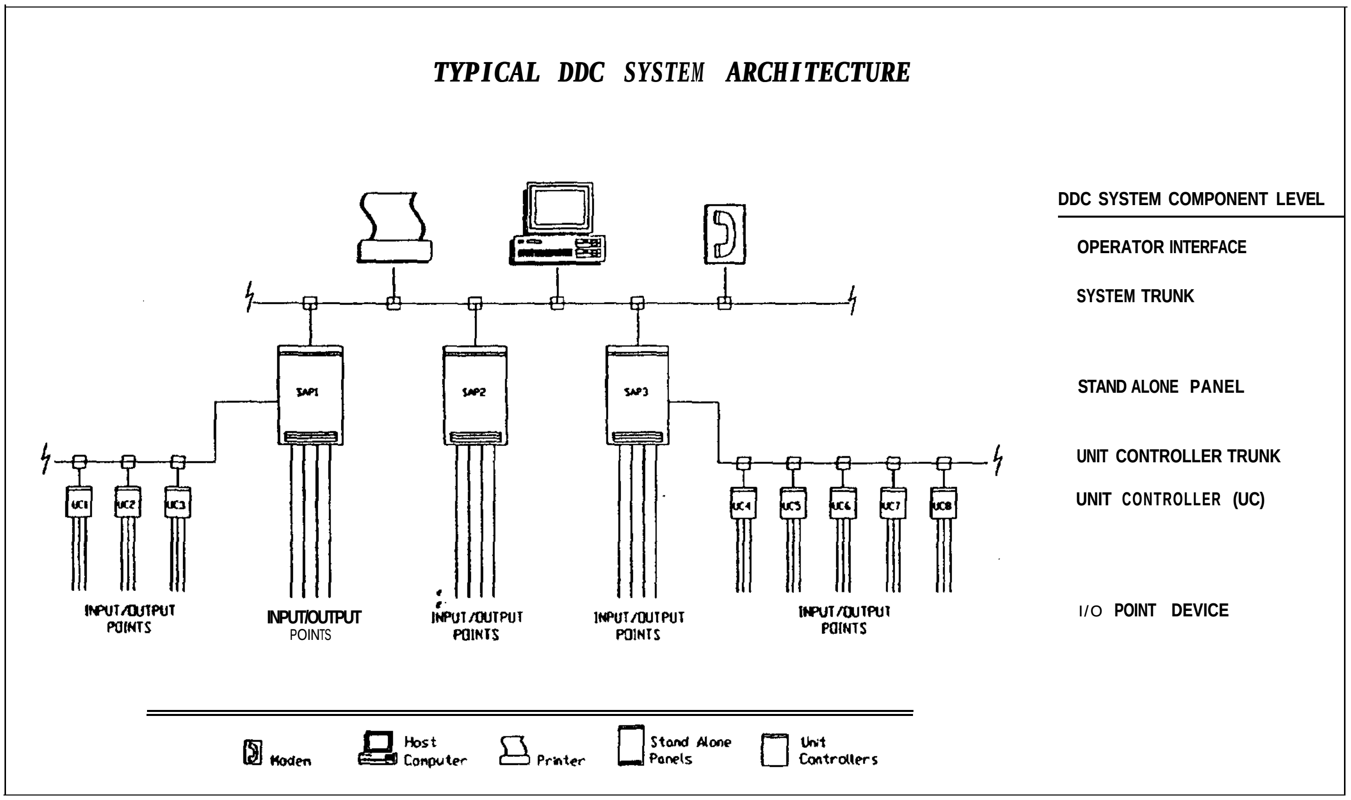

Figure 6

new generation of DDC systems has been developed (Hartman 1990-91), but selecting the control system that will operate successfully in a fully integrated HVAC and lighting control environment is still a perilous task. Each of the thousands of points that may be required for an integrated control system must be capable of being individually operated by distributed custom programs. These points and thousands more program variables all must have access to a high-speed automatic network that can exchange information about any point, variable, or program within several seconds in a fully loaded operational environment. The designer must be both knowledgeable and careful to ensure the mechanical design and the DDC system will actually perform as expected. To illustrate the potential difficulties, Figure 6 diagrams the typical architecture of modem full-DDC systems today. The DDC system items most important for an integrated controls design that is suitable for TRAV operation are

- uniform distributed control,
- automatic networking and
  high-speed communications, and
- a powerful operators' control language (OCL).

While most DDC systems possess distributed control architecture, only a few provide "uniform" distributed control. In many DDC systems, "points" connected to the stand alone panels (SAPs) and unit controllers (UCs) generally require different techniques for programming, calibrating, and operator interfacing. In some systems, the points in the UCs are operated by fixed read-only memory (ROM) programs and cannot be operated by custom algorithms at all. These systems are usually unsuitable for TRAV applications. Another problem is the lack of uniformity of control function among points that are connected to SAPs and UCs. One crucial element in TRAV control is the ability to read the value of the output to the box damper or reheat valve and, under certain circumstances, to limit its travel within the normal PID operation. While this is usually easy to accomplish with points connected to SAPs, it may be difficult or impossible with many of the associated UCs. The resulting differences in performance between SAPs and UCs can make many DDC systems appear more like two separate systems, one consisting of the SAPs and the points connected to them, and the other consisting of UCs and their connected points.

Many DDC systems also lack a high-speed communications network that can provide all the communications required among the controllers for effective TRAV operation. A TRAV design requires prompt and direct communication between the program controlling the central fan speed and the flow conditions at each of the boxes supplied by the fan. It is not usually feasible to try to operate such systems on slow networks, nor is it reasonable to require a programmer to "build" the required network of points that must communicate with one another. The term "automatic networking" is used to describe those networks that automatically add points or variables in each controller to the network configuration as programs that employ those points are entered into other controllers. The operator or programmer can envision such a configuration as a single integrated entity instead of a large number of individual parts. Automatic high-speed networking is essential to successful TRAV applications. It is surprising how much communication is required for effective TRAV operation and how few DDC systems have the capacity to provide such networking capabilities.

Finally, a suitable programming language must be a part of the DDC system in order to construct the algorithms necessary to implement TRAV and the related control improvements listed in this paper. A functional and flexible operators' control language (HC 1989) is required to construct effective TRAV control algorithms.

The difficulties associated with implementing a DDC system that combines truly uniform distributedcontrol along with a high-speed automatic network and the Rower to execute dynamic control strategies is still a serious issue for designers and one that deserves continuing attention from all DDC system manufacturers as well.

A TRAV CASE STUDY

TRAV retrofit designs that include the elements described above have recently been implemented in several buildings. The case study building is a high-rise office building approximately 350,000 square feet in area. The building was constructed in 1982. It is an all-electric building that employs floor-by-floor VAV. Originally the building had standard VAV with inlet vane control of airflow. Cooling is provided by Direct expansion air conditioning units on each floor rejecting heat to a common condenser water/cooling tower circuit. Heating is provided at the perimeter by parallel fan-powered boxes with electric reheat. A relief fan with a scroll damper on each floor is operated to maintain floor static pressure. The building is located in Bellevue, Washington.

The building envelope is a curtain wall with double-glazed windows throughout the building. Lights were operated with standard line voltage wall switches. There are two lighting circuits (with wall switches) in each perimeter office to permit occupants to adjust the lighting level

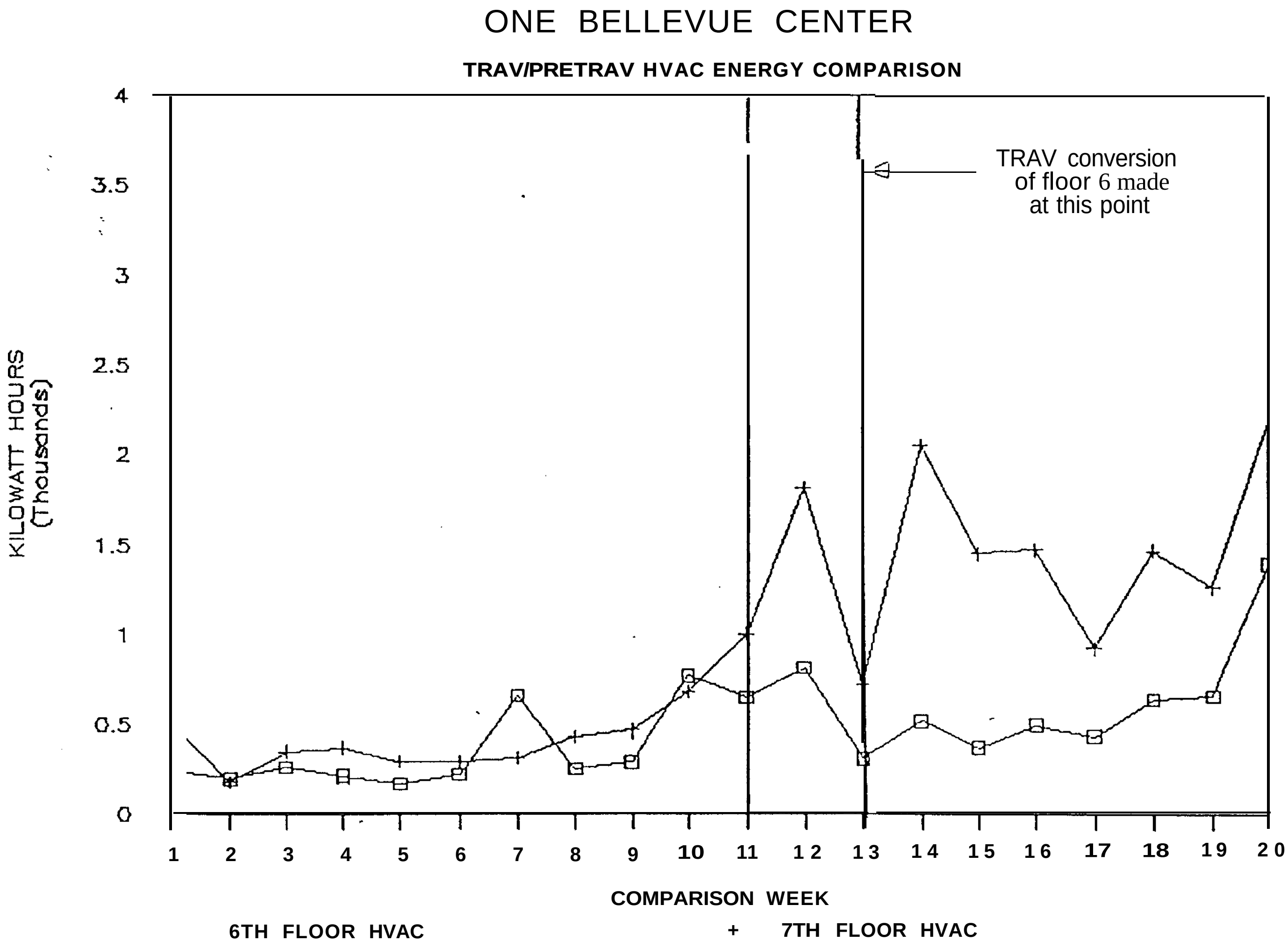

Figure 7

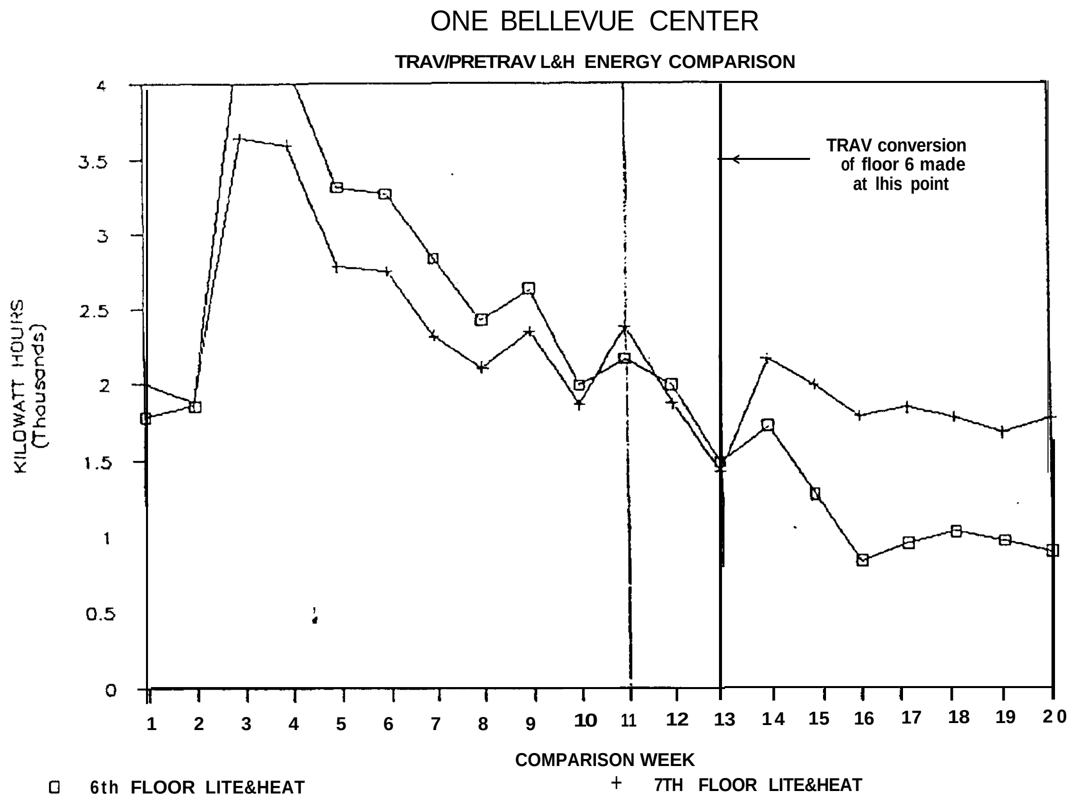

Figure 8

according to sun conditions. The original connected lighting load was approximately 1 W/ft^2. Recent energy use for the building totaled about 62,000 Btu/ft^2/yr.

THE TRAV RETROFIT DESIGN

Analysis by an in-house hourly building simulation program indicated that this building was a good candidate for a TRAV retrofit despite its better-than-average energy use figures. Our estimate of energy use under TRAV operation for this building was about 35,000 Btu/ft^2/yr.

The TRAV design effort for the building focused on the terminal control aspects of the system. The owner agreed that every office should be equipped with a space temperature sensor and a pushbutton occupancy control device (pushbuttons were employed instead of occupancy sensors because of cost considerations). A lighting relay operated by the DDC system was installed to control the lights in each office and open area. The result is that each VAV terminal box now has, on average, more than two space temperature sensors associated with its operation.

The owner decided to initially retrofit just one floor of the building to TRAV operation and to monitor this and one other floor so that the actual savings could be accurately assessed. For this pilot project, the owner chose two floors of equal size that were part of a single tenant's space. The occupancy patterns and partitions on both floors were very similar.

Electric metering was installed in advance of the retrofit, and the retrofit was accomplished during off hours without disrupting the tenants. There were no changes in occupancy patterns on either floor throughout the duration of the monitoring effort. The metering consisted of three meters. One meter on each floor monitored plug load. A second meter monitored the fan and DX cooling load. The third meter monitored the lighting and electric heating loads. After the meters were installed, it was found that the upper floor had a higher plug load than the lower floor. It was decided to make the floor with the lower plug load the TRAV retrofit floor and to average the plug loads for both floors in energy use comparisons.

The retrofit of the test floor was very straightforward and was easily accomplished during off hours while the spaces remained occupied. The pneumatic box damper actuators were replaced with electric actuators. An airflow sensor was installed just ahead of the air valve at each box, and the fan and reheat coil of each perimeter box were connected to the DDC system.

The supply fan on the floor was fitted with a variable-frequency-drive and was operated by the DDC system to meet the airflow requirements at each terminal box in accordance with TRAV principles. The floor's DX compressor and staging valves were also connected to the DDC system, as well as the relief fan, mixing air dampers, and other HVAC and lighting control elements.

The results of the TRAV retrofit on the pilot floor were dramatic. Figure 7 shows the fan and cooling energy comparisons, and Figure 8 shows the lights and reheat energy use for the two floors before and after the TRAV retrofit. The conversion took place at the end of May as the season changed from heating to cooling. The figures show that the TRAV conversion floor had overall higher HVAC and lighting energy use before the retrofit, but substantially lower energy use after the conversion. Energy reductions exceeded the projected savings levels. Long-term monitoring confirms these findings. Actual annual monitored energy use for the pilot floor after the TRAV retrofit was 8.2 kWh/ft^2 total annual energy use while the adjacent floor continued at the building average of 16.7 kWh/ft^2. After adjusting the figures for energy overhead items such as elevators and parking garage lighting, the TRAV floor is still using less than 10 kWh/ft^2 per year, an approximately 50% reduction in energy use for a building that was already operation at below average energy use.

Equally dramatic is the significant improvement in comfort noticed by the occupants on the TRAV floor. No formal survey has been made since the TRAV retrofit but the building manager and his technicians have heard occupants laud the improvements during elevator conversation. The owner was sufficiently pleased with the results to begin immediately on the remaining 20 floors of the building. That project is now approaching completion.

Total estimated energy savings for the building once TRAV has been extended to all floors is approximately 2.6 million kWh annually. The cost of implementing the full-building TRAV configuration is $1 million. The serving electric utility is participating in this project by paying for a portion of the cost of the project.

SUMMARY AND RECOMMENDATIONS

Terminal regulated air volume-based building mechanical systems offer significant improvements in energy efficiency and comfort. The primary innovation of TRAV systems is not the mechanical components, but the manner in which the mechanical system operates. The high level of success that TRAV has enjoyed in the early projects should encourage designers and building owners to investigate the employment of TRAV and its related design innovations in their new and retrofit building designs. To that end this paper recommends building owners and design engineers take the following steps to better implement high-performance DDC systems in their HVAC designs:

1. Expend time and effort to become more knowledgeable about the various high-performance DDC systems that are available and will soon be available. Remember that many DDC sales engineers are not experienced with providing the in-depth information necessary for designers to develop high-performance controls designs.
2. Designers should work to include as many of the successful new approaches described in this paper as are applicable to their individual project. The primary innovations include:
   - terminal regulation of fan speed, continuous HVAC system operation, integration of lighting and HVAC control, lighting and comfort zones sized no larger than a single office, and improved VAV box control strategies.
3. Designers should take a larger role in the design and implementation of the HVAC system and especially the DDC portion of the project. Designers should develop the controls design and drawings as a part of their mechanical design effort.

REFERENCES

Englander, S.L. 1990. *Ventilation controls for energy conservation: Digitally controlled terminal boxes and variable speed drives.* Center for Energy and Environ*mental* Studies, Princeton University

Hartman, T. 1990-91. DDC controls today. *Heating/Piping/Air Conditioning,* November - January.

Hartman, T. 1989. TRAV-A new HVAC concept. *Heating/Piping/Air Conditioning,* July.

Hartman, T. 1988. Dynamic control: A new approach. *Heating/Piping/Air Conditioning,* April - December.

HC. 1988. *Operators' control language, a guide to programming function for DDC systems,* Seattle: The Hartman Company.

von Thun, G., and M.J. Witte. 1991. Applying building simulation tools to optimize system sizing and operation strategies. *ASHRAE Transactions 97(l).*