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The Use of Multipoint Monitoring as a Tool for Commissioning Buildings for IAQ

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ABSTRACT

One basic goal of the commissioning process is to make sure that the HVAC system is functioning as intended. In particular, it is intended that the HVAC system not only provide adequate ventilation for the building occupants but also achieve adequate pressurization of the occupied spaces to prevent the infiltration of unconditioned air. One technique for evaluating the performance of the HVAC system in these areas is to use continual, multipoint monitoring of carbon dioxide, carbon monoxide, and dew point at selected locations in the building and the HVAC system.

Specific performance evaluations provided by multipoint continual monitoring of these parameters include a determination of the amount of outdoor air delivered to the occupants for ventilation, an evaluation of the uniformity of the amount of ventilation provided to the different locations served by a given air-handling unit (AHU), an evaluation of the adequacy of the system operation in completely purging the building overnight of air contaminants from the previous day's occupancy, the identification of the infiltration of unconditioned air into occupied spaces, the identification of the magnitude and frequency of reentrainment of building exhaust, and the identification of the magnitude and frequency of the introduction of vehicle exhaust from nearby traffic.

Specific examples of all of these performance evaluations are presented and discussed in this paper. In addition, these ongoing evaluations of system performance can not only identify the presence of problems but can also evaluate the effectiveness of mitigation efforts to correct and eliminate these problems. The use of continual, multipoint monitoring of these parameters, therefore, can yield improved indoor air quality (IAQ) in buildings from initial occupancy throughout their useful life.

INTRODUCTION

One building practice with significant impact on commissioning, operation, maintenance, and indoor air quality (IAQ) is the use of continual monitoring of IAQ parameters. This is because this monitoring provides feedback on the performance of the HVAC system in many areas. Information is provided not only on ventilation performance but also on pressurization for infiltration control, humidity control, the occurrence of reentrainment, and the detection of air contaminants from nearby motor vehicles.

Since building commissioning performed in new construction and existing buildings helps to ensure that systems are installed, functionally tested, and capable of being operated and maintained to perform in conformity with the design intent and owner's needs (ASHRAE 1996), it is very useful to have feedback on the performance of the HVAC system.

MONITORING OF IAQ PARAMETERS

The monitoring of IAQ parameters in buildings provides feedback on HVAC performance. The key parameters for IAQ that can be measured include carbon dioxide (CO_2), carbon monoxide (CO), and dew point (absolute humidity). There are several ways to collect measurements of these parameters. Monitoring can vary from a few grab-samples to one monitor at one location, several monitors at several locations, all the way to a shared-sensor system with sampling lines from 24 or 48 locations. They all can contribute information on system

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performance. The success of the commissioning process is directly proportional to the amount and quality of data collected.

Continual monitoring has several advantages over grab-sampling. One difference is that with continual monitoring there can be confidence that peak values were recorded; grab-samples may, or may not, reflect peak values. The collection of peak values for CO_2 concentrations are important for the assessment of ventilation adequacy. Also, data from repeated measurements throughout the day provide information on whether equilibrium conditions were achieved. It is also valuable to have a dynamic picture of ventilation performance that is created by sequential sampling of the multiple sampling locations so as to achieve more insight into understanding the subtle details of the ventilation system's capabilities.

The accuracy of data from the monitors is also very important. This is especially true for the data on CO_2 concentrations, both because these sensors are very vulnerable to drift and also because the quality of the evaluation assessment will be a direct function of the accuracy of the recorded CO_2 values. A potential problem exists with hand-held monitoring devices that can be influenced by human breath, which contains approximately 38,000 ppm of CO_2. If only 1% of the investigator's breath is included in the air being measured, an actual background concentration of 800 ppm will be indicated as 1,172 ppm. If distributed sensors are used for data collection, this may introduce a source of error, as different responses among detectors may indicate differences where none exist or may fail to indicate an actual difference that does exist. Similarly, the number and selection of sampling locations will also affect how representative the data collected are and how definitely it can assess the ventilation performance in a building.

The various approaches available for monitoring programs, therefore, need to be given careful consideration. If just grab-samples are collected, the instrument needs to be checked periodically for accuracy and the operator needs to be trained to prevent his exhaled breath from affecting the CO_2 readings. With a series of distributed monitors, the potential for drift and the need for periodic recalibration can compound the cost and complexity of a monitoring project. However, all of these problems can be conveniently dealt with by using a shared sensor system connected to an array of many sampling lines. In addition, delivering air samples from multiple locations to just one sensor will indicate the response characteristics of the detector. This will provide not only a simple calibration check during off-hours, but it will reveal whether or not the sensor has failed or not. An example of a sensor that failed in a shared sensor system is presented in Figure 1. Its random and inconsistent responses can be seen easily. In contrast with the shared-sensor results shown in this figure, an individual wall-mounted remote sensor would not provide such blatant evidence of its failure. This increase in data integrity is but one example of the difference between using a shared-sensor system and distributed individual monitors.

In the monitoring system with which the author is familiar, the equipment permits up to either 24 or 48 point configurations. While this system could be used in any building, the cost/benefit ratio is more attractive in buildings that are at least 100,000 ft^2 in area. The total cost of the system is composed of three elements: the cost of the monitoring system itself, the labor and materials for installing the sampling lines, and management fees for the project. The project management fees include such components as the supervision of site preparation, the ongoing data collection effort, and the interpretation of data. While the specifics of each installation have

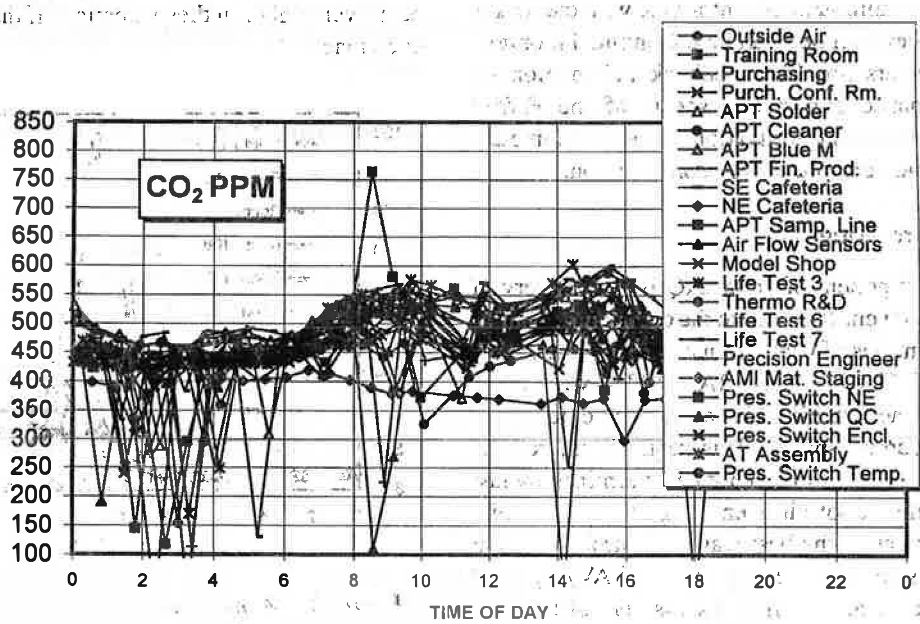

***Figure 1** Example of failed sensor.*

varied, the total cost for a number of installations have cost less than $50,000. These installations have been in both new construction and retrofits. They have also varied from permanent installations to short-term (six-week) installations for occasional investigations of ventilation system performance. The three parameters currently available are carbon dioxide, carbon monoxide, and dew point (absolute humidity). One installation also looked at VOCs as part of a special research effort. While this parameter is not currently available as a standard option, it does point out the flexibility of the system in being able to incorporate other sensors. It should be noted that temperature cannot be included as a sampling parameter because the air sample delivered to the sensors first passes through a vacuum pump, which would raise its temperature beyond that of the space being monitored.

In addition to the monitoring of CO_2 concentrations, the other IAQ parameters help assess HVAC system performance. Monitoring for CO can quantify the presence of this air contaminant from incomplete combustion, both from the perspective of its local control and possible infiltration to occupied areas of the building. Monitoring for dew point can assess the effectiveness of humidity control in the building, as well as the presence of interior sources of moisture and the infiltration of unconditioned air from outdoors.

COMMISSIONING OF BUILDINGS

Commissioning involves procedures and methods for documenting and verifying the performance of HVAC systems so that they operate in conformity with the design intent (ASHRAE 1996).

While the design intent focuses on the achievement of the ventilation objectives, it is important also for the HVAC systems to function as intended. To achieve this, the operators must be trained to be familiar and comfortable with the details of the system that they will be operating. Continual monitoring of IAQ parameters provides feedback information on ventilation performance and other aspects of the HVAC system that can facilitate the evaluation of these parameters for both IAQ management and energy consumption.

Ventilation Performance

A necessary component of good IAQ is the delivery of adequate quantities of ventilation air to the occupants of buildings. Minimum quantities of ventilation air are listed in *ANSI/ASHRAE Standard 62-1989* (ASHRAE 1989) where one component of IAQ acceptability is the rate of outdoor air delivery to the occupied spaces. This requirement for the delivery of adequate ventilation cannot be determined by just knowing how much outdoor air is entering the AHU. While there is some debate as to the best way to control minimum ventilation volumes in variable-air-volume (VAV) systems (Kettler 1998), what is needed is an assessment of how the occupied spaces are being ventilated rather than just how much air is entering the HVAC system. Continual, multipoint monitoring of carbon dioxide (CO_2) concentrations can provide the information needed to make this determination.

It should be noted that CO_2 itself is not considered to be capable of causing adverse impacts on people in the concentrations that typically are experienced in office spaces. But, just as the CO_2 builds up, so can the other potentially irritating chemical compounds present in offices, and it is these that can cause symptoms of "sick building syndrome." The value of CO_2 monitoring, therefore, comes from its status as an indicator of ventilation performance.

Unlike grab-sampling, where CO_2 samples are collected at different locations in the building at different times, continual monitoring at key locations makes sure that peak values are recorded. It is these peak values and their duration that are needed for determining ventilation rates. In addition, since sampling of the outdoor air is typically included among the locations selected in a continual, multipoint monitoring system, the difference in CO_2 concentrations between the indoors and outdoors is automatically provided. This indoor/outdoor differential is an essential component of the ventilation assessment. A reading just of the indoor CO_2 value falls short of the requirement. An example of the data provided by a shared-sensor, multipoint monitoring system is presented in Figure 2. A lot of information on ventilation performance is provided in this figure. Most noticeable perhaps are the peaks for Rooms 178 and 112, both training rooms, which exceed 2,000 ppm of CO_2. In conjunction with a reading of 350 ppm of CO_2 for the outdoor air, this corresponds to a ventilation rate of approximately 6 cfm of outdoor air per person. This calculation may actually overstate the amount of ventilation provided because it is not clear whether equilibrium conditions have been achieved in this situation. The question remains as to whether the CO_2 concentrations would have been even higher in these locations if the occupancy persisted even longer.

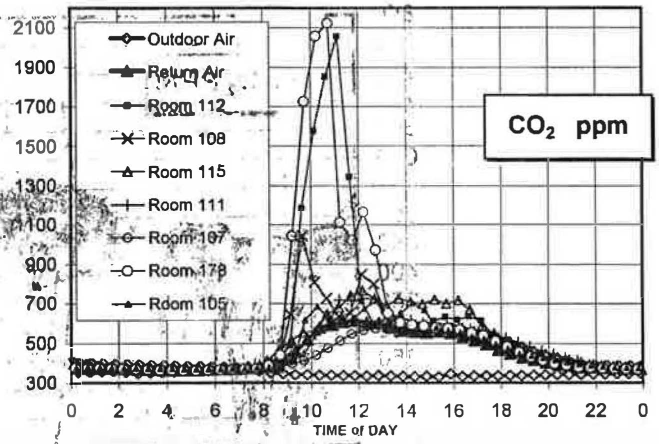

***Figure 2** Monitoring data indicating distribution inefficiency, July 2, 1997; locations served by AHU 2.*

Distribution Inefficiency

Also observable in this figure is the fact that the rest of the building is very generously ventilated. This conclusion can be reached by examination of the other locations displayed on this figure. All of the sampling locations presented in this figure are for AHU 2. This data plot clearly indicates the presence of a distribution problem in getting adequate ventilation to a portion of the space served by this AHU. A similar situation would result if the VAV system had its minimum set too low.

It is important to note that the CO_2 value for the return air to this AHU fails to provide an indication of the distribution problem. The CO_2 value for the return air only reflects, at best, an average of the values for the spaces from which it is drawing air. Therefore, the CO_2 concentrations in the return air should not be used for demand-controlled ventilation (DCV) in situations where an AHU serves multiple spaces with different occupancy densities. In such cases, it would fail to assess whether adequate ventilation is being provided in all of the occupied spaces.

Ventilation Adequacy

The relationship between CO_2 concentrations and ventilation rates depends on the mass of the people, their diet, and their activity level. The example given here is for adults doing office work. Another way of considering the relationship between peak CO_2 concentrations and ventilation rates is to determine the indoor/outdoor differential that should not be exceeded if adequate ventilation is provided. For instance, if this difference were 500 ppm or less (i.e., 900 ppm indoors and 400 ppm outdoors), it would correspond to a ventilation rate of at least 20 cfm of outdoor air per person. Therefore, as long as peak values indoors are less than 500 ppm more than the outdoor value, the ventilation goal of Table 2 in ASHRAE Standard 62 would be achieved.

An issue related to the adequacy of the ventilation provided is the functioning of the distribution system of the HVAC system. Continual monitoring of CO_2 concentrations can also provide a dynamic assessment of the relationship between how the system is balanced and the actual distribution of people in the spaces served by a given AHU. This is important because the number of people and their distribution changes continually in buildings. Therefore, CO_2 concentrations will also vary by location, by time of day, and by day in buildings as a function of both the ventilation performance and the occupancy patterns.

Another criterion for ventilation performance is that the air contaminants from the previous day's occupancy be completely purged prior to the next morning. Again, continual monitoring of CO_2 concentrations can also provide an assessment of HVAC performance with respect to air contaminants of human occupancy. With incomplete purging, a differential between the indoor and outdoor CO_2 concentrations still remains at the time of reoccupancy the next day. An example of this condition is presented in Figure 3. For this building, the outdoor air percentage was maintained at 19% through the day. This fact was determined by a mass balance equation involving the CO_2 concentrations in the outdoor air, return air, and supply airstreams. One can also note in this figure that the CO_2 value recorded for the return airstream is lower than any of the occupied spaces measured. Also observable in Figure 3 is the variability of the CO_2 concentrations, reflecting the dynamic interaction between the amount of ventilation provided and the number of people in each occupied space.

With a higher percentage of outdoor air or a longer duration of operation, the indoor/outdoor differential can go to zero

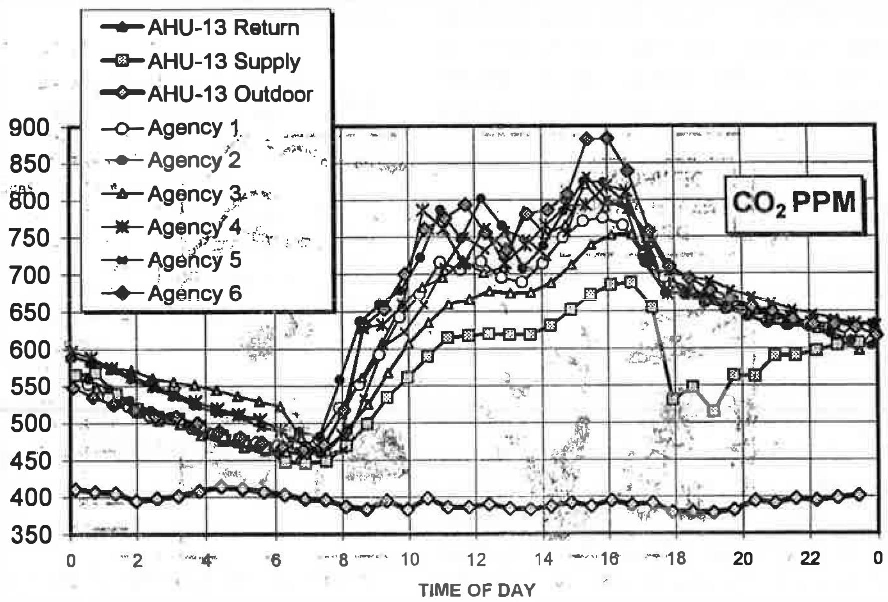

Figure 3 Federal office building 1, May 23, 1996, AHU 13 only.

in an overnight purge cycle. How quickly this indoor/outdoor difference goes to zero reflects how leaky the building is or how generous the ventilation operation is. Figure 2 presents an example of the rapid disappearance of this differential, reflecting in this new building a generous amount of ventilation.

OTHER ASPECTS OF HVAC PERFORMANCE

Other aspects of HVAC performance include the ability of the system to maintain humidity control and to prevent the reentrainment of building exhaust, the introduction of nearby vehicle exhausts, and the infiltration of unconditioned outdoor air. Infiltration of unconditioned air into buildings, normally prevented by maintaining perimeter areas of buildings at a positive pressure to the outdoors, will be reflected in the data from any of the three IAQ parameters. For the CO_2 data, however, the infiltration of outdoor air will yield the same low values as those due to low occupancies or generous HVAC ventilation.

Monitoring of Carbon Monoxide Concentrations

The measurement of CO concentrations in occupied areas can indicate whether the HVAC is containing, isolating, and removing air contaminants from vehicle exhausts in loading docks or parking areas at the base of the building. An example of successful control of CO is provided in Figure 4. For this building, the rapid decrease in CO concentrations reflects the effective functioning of the exhaust systems in the loading dock and underground parking garage. The absence of elevated CO values in any of the measured occupied locations reflects the effectiveness of the pressurization of these areas, thus providing control against infiltration.

Another building monitoring installation that included the measurement of CO detected the after-hours intrusion of inadequately exhausted emissions (i.e., they failed to be discharged above the roof level) from gas-fired combustion appliances in the building next door. Having identified the problem, this monitoring system was then able to evaluate the effectiveness of various mitigation efforts implemented to correct this IAQ problem.

Monitoring of Humidity Values

The monitoring of absolute humidity values by measuring dew-point temperatures both indoors and outdoors will detect infiltration if it occurs during those times when there is a difference between the outdoor value and most of the indoor values. Figure 5 provides an example of such a situation. For this building, it is the loading dock that is experiencing this

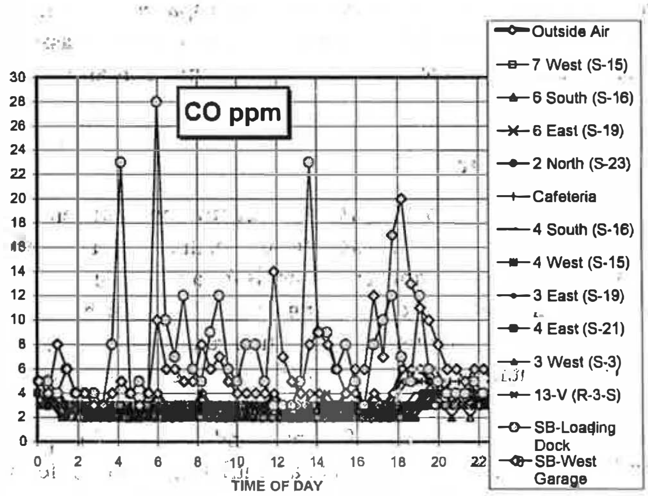

Figure 4 Office Building TNE, carbon monoxide on May 2, 1997.

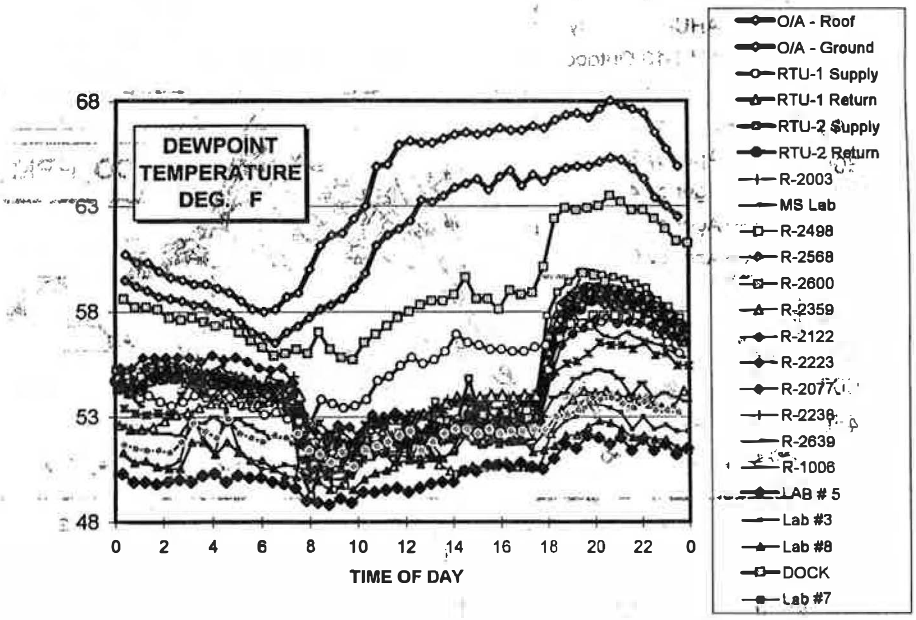

Figure 5 Stratus computer, June 19, 1995.

infiltration. As observed in Figure 5, this is determined by the fact that absolute humidity for this dock is partway between those for the outdoors and those for the rest of the building. Also observable in this figure is the difference in absolute humidity for the two outdoor locations. The humidity for the ground level location is higher than for the rooftop location. This difference can be explained by the existence of moisture emanating from the ground, and it also indicates the benefit of sharing one high-quality humidity sensor among all of these locations. The monitoring of dew-point temperatures will also provide feedback on the performance of humidity control in the building. Again, monitoring of this parameter using a shared sensor approach permits the use of an expensive, high-quality sensor for all of the locations, making the achievement of quality data cost-effective.

Another condition observable in Figure 5 is that the measured value for RTU-1 supply is higher than for the rest of the building. This condition indicates that there is a problem with this AHU, either internal leakage bypassing the cooling coil, or a refrigeration (dehumidification) problem with this coil, or more latent moisture from the outdoor air, or an internal load. Again, this monitoring system can not only identify when the HVAC system is not operating as intended but it can determine when problems have been corrected.

The importance of this monitoring of humidity control reflects both the high maintenance aspect of systems that add humidity to the indoor air and the risk of microbiological growth caused by the presence of excess moisture indoors. Thus, monitoring systems that include the measurement of dew point can not only provide feedback for commissioning but can also detect the presence of indoor sources of moisture.

The indoor sources of moisture may be benign, such as the choral group rehearsing in Room 340 (see Figure 6), or it may have energy consequences due to steam leaks, or have microbiological IAQ consequences due to otherwise unknown water leaks.

Monitoring for Reentrainment

Reentrainment of exhaust air back into a building's outdoor air intake will also be reflected in continual CO_2 monitoring. If reentrainment is occurring, it will be reflected in the plot of CO_2 concentrations measured at the outdoor air intake. In the absence of reentrainment, the CO_2 values for outdoor air will be stable throughout the day at about 340 ppm to 400 ppm. If reentrainment is occurring, this will be reflected in this plot for the outdoor air looking like a dampened mirror image of the interior building values. An example of reentrainment is provided in Figure 7. The similarity of the outdoor air values to the other building values reflects the magnitude of reentrainment. The frequency of this occurrence will be reflected in the monitoring data.

Monitoring for the Entrainment of Nearby Vehicle Exhausts

The entrainment of nearby vehicle exhausts by a building's outdoor air intake will also be reflected in the plot of CO_2 concentrations. As with reentrainment, this condition is reflected by elevations in the CO_2 values recorded in the outdoor airstream—in this situation, the increases in the outdoor air CO_2 values occur at the time of the peak morning and afternoon commuter traffic. An example of this condition is shown in Figure 8.

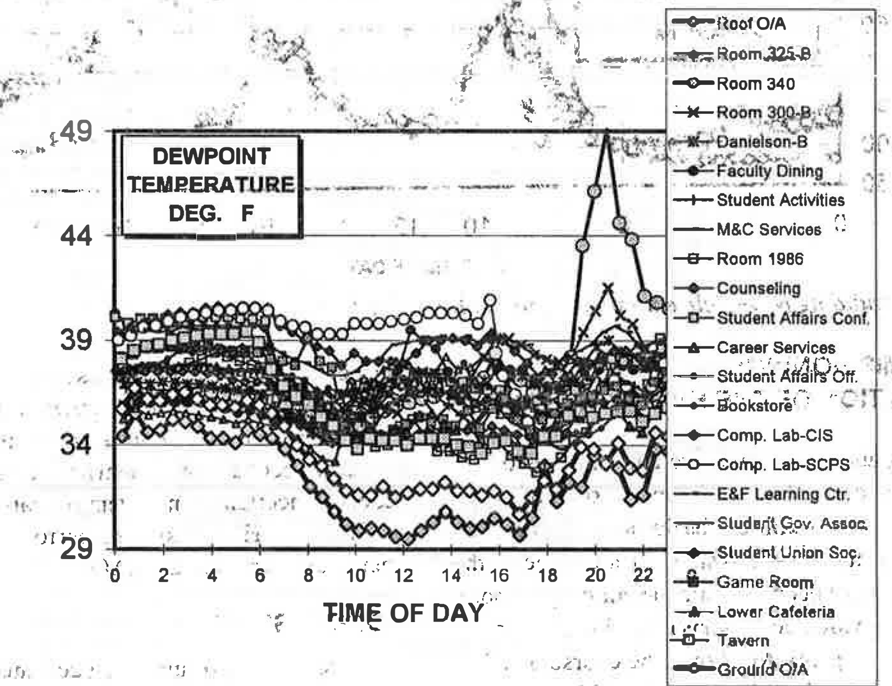

Figure 6 *College student center with interior source of moisture.*

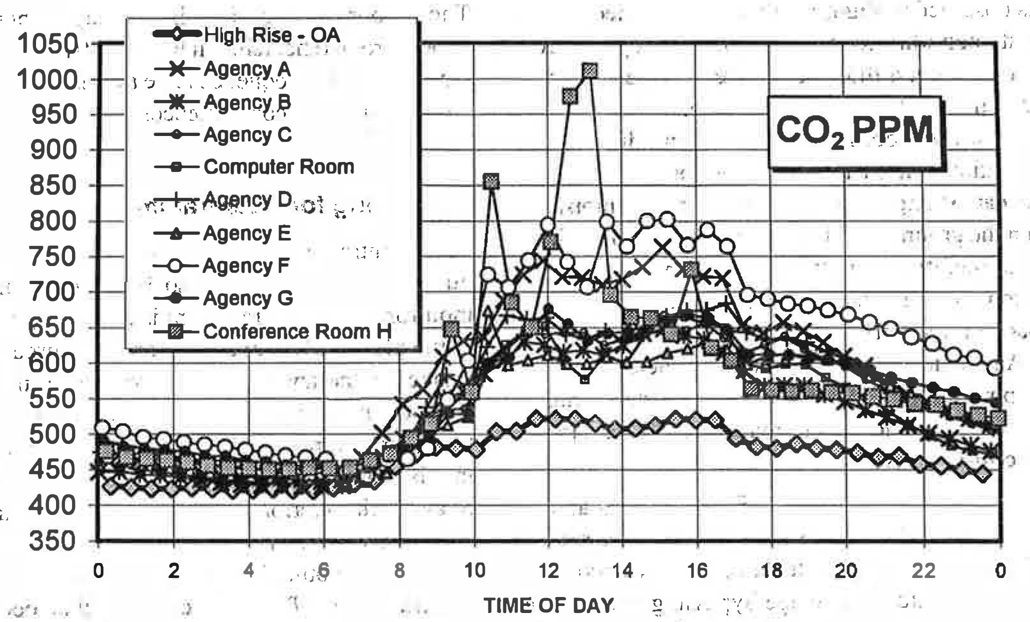

Figure 7 Federal office building 1, reentrainment, March 26, 1996.

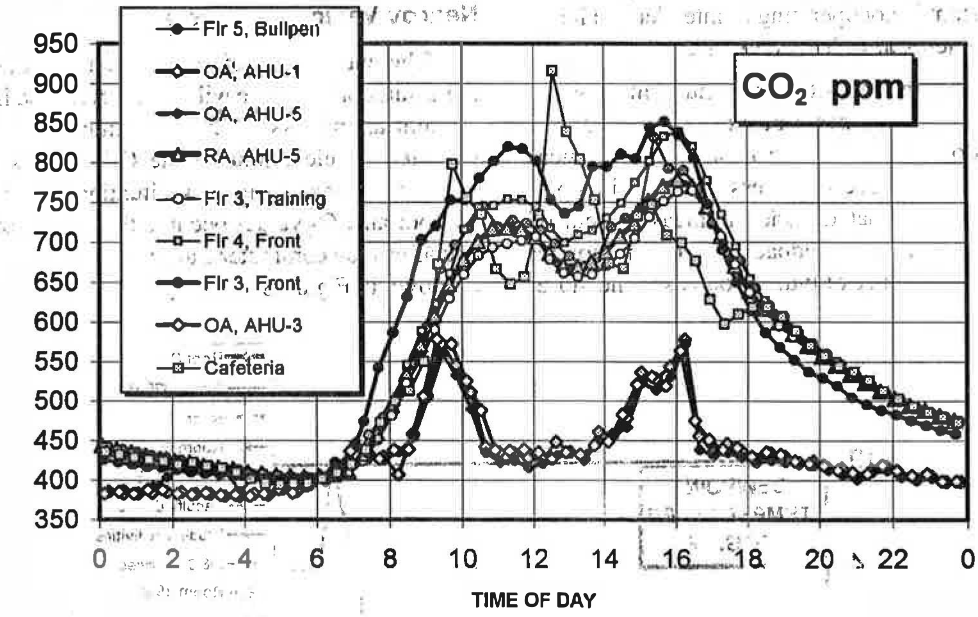

Figure 8 Office building N, vehicle emission capture, March 10, 1994.

ONGOING COMMISSIONING: OPTIMAL OPERATION OF THE HVAC SYSTEM

As the building and its systems age and the uses of the building change, the potential exists for the amount of ventilation to become inadequate. This can be due to either a change in the performance of the HVAC system, or a change in the number and distribution of people within the building, or both. Figure 9 illustrates the wide fluctuations in outside air percentages that can occur for a given AHU over the course of a day. By monitoring fundamental IAQ parameters either periodically or continuously, feedback on ventilation performance can not only detect deficiencies in ventilation performance but can also guide remediation strategies and projects and assess the effectiveness of efforts to mitigate deficiencies. This degree of feedback on system performance, therefore, not only reduces uncertainty in system operation but can also be used to fine-tune HVAC system performance to optimize both energy conservation and IAQ.

CONCLUSIONS

The practice of including continual, multipoint monitoring of IAQ parameters provides valuable benefits in the commissioning, IAQ evaluation, operation, and maintenance

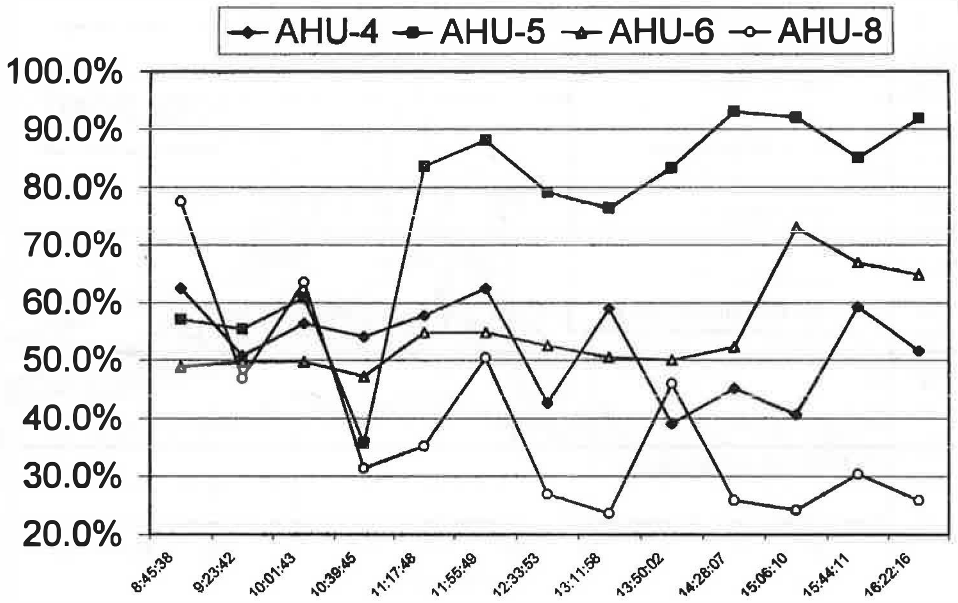

Figure 9 *Federal office building 2, April 10, 1998, outdoor air percentages.*

of a building by providing information on HVAC performance. By providing such feedback where none had been available before, this information on ventilation performance reduces operational uncertainties and helps maximize the health, comfort, and productivity of occupants.

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