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Demand-Controlled Ventilation Using CO_2 Sensors

Preventing energy losses from over-ventilation while maintaining indoor air quality

Executive Summary

Demand-controlled ventilation (DCV) using carbon dioxide (CO_2) sensing is a combination of two technologies: CO_2 sensors that monitor CO_2 levels in the air inside a building, and an air-handling system that uses data from the sensors to regulate the amount of ventilation air admitted. CO_2 sensors continually monitor the air in a conditioned space. Given a predictable activity level, such as might occur in an office, people will exhale CO_2 at a predictable level. Thus CO_2 production in the space will very closely track occupancy. Outside CO_2 levels are typically at low concentrations of around 400 to 450 ppm. Given these two characteristics of CO_2, an indoor CO_2 measurement can be used to measure and control the amount of outside air at a low CO_2 concentration that is being introduced to dilute the CO_2 generated by building occupants. The result is that ventilation rates can be measured and controlled to a specific cfm/person based on actual occupancy. This is in contrast to the traditional method of ventilating at a fixed rate regardless of occupancy.

Building codes require that a minimum amount of fresh air be provided to ensure adequate air quality. To comply, ventilation systems often operate at a fixed rate based on an assumed occupancy (e.g., 15 cfm per person multiplied by the maximum design occupancy). The result is there often is much more fresh air coming into buildings than is necessary. That air must be conditioned, resulting in higher energy consumption and costs than is necessary with appropriate ventilation. In humid climates, excess ventilation also can result in uncomfortable humidity and mold and mildew growth, making the indoor air quality (IAQ) worse rather than better.

A lack of adequate fresh air, on the other hand, can make building occupants drowsy and uncomfortable. To avoid the problems of too much or too little fresh air, the heating, ventilation, and air-conditioning (HVAC) system can use DCV to tailor the amount of ventilation air to the occupancy level. CO_2 sensors have emerged as the primary technology for monitoring occupancy and implementing DCV. Energy savings come from controlling ventilation based on actual occupancy versus whatever the original design assumed.

Handheld CO_2 sensor with data logging.

Application Domain

CO_2 sensors have been available for about 12 years. An estimated 60,000 CO_2 sensors are sold annually for ventilation control in buildings, and the market is growing. There is a potential for millions of sensors to be used, since any building that has fresh air ventilation requirements might potentially benefit from the technology.

CO_2-based DCV has the most energy savings potential in buildings where occupancy fluctuates during a 24-hour period, is unpredictable, and peaks at a high level—for example, office buildings, government facilities, retail stores and shopping malls, movie theaters, auditoriums, schools, entertainment clubs and nightclubs.

CO_2 sensors are considered a mature technology and are offered by all major HVAC equipment and controls companies. The technology is recognized in ASHRAE Standard 62, the International Mechanical

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Code (which establishes minimum regulations for mechanical systems), and some state and local building codes. Although the first CO_2 sensors sold were expensive, unreliable, and difficult to keep calibrated, manufacturers say they have largely resolved those problems. The unit cost of sensors has dropped from \$400 to \$500 a few years ago to \$200 to \$250 (not including installation). As market penetration increases, prices are expected to fall further.

Several manufacturers produce CO_2 sensors for DCV. Most manufacturers of thermostats and economizers are integrating CO_2 sensors into their products, and major manufacturers of packaged rooftop HVAC systems offer factory-installed CO_2 sensors as an option.

Benefits

DCV saves energy by avoiding the heating, cooling, and dehumidification of more ventilation air than is needed. CO_2 sensors are the most widely accepted technology currently available for implementing DCV. Additional benefits of CO_2-based DCV include

- Improved IAQ—By increasing ventilation if CO_2 levels rise to an unacceptable level,
- Improved humidity control—In humid climates, DCV can prevent unnecessary influxes of humid outdoor air that makes occupants uncomfortable and encourages mold and mildew growth.

Estimated Savings

The potential of CO_2-based DCV for operational energy savings has been estimated in the literature at from \$0.05 to more than \$1 per square foot annually. The highest payback can be expected in high-density spaces in which occupancy is variable and unpredictable (e.g., auditoriums, some school buildings, meeting areas, and retail establishments), in locations with high heating and/or cooling demand, and in areas with high utility rates.

Design Considerations

CO_2 sensing is a fairly simple technology, and installation of the sensors themselves is not complicated. Including CO_2-based DCV in a new HVAC installation should not add significantly to the difficulty of commissioning the system. However, retrofitting an existing system for DCV may be more problematic, particularly for an older system with pneumatic controls. Applying a CO_2-based DCV strategy using ASHRAE 62 is more complicated than simply installing CO_2 sensors and using them to control dampers. In variable-air-volume systems, particularly, fairly complex calculations and control algorithms may be necessary to program the control system properly for DCV. The use of a more complex control algorithm often provides increased savings and improved IAQ; while it increases the level of commissioning, the results outweigh the extra initial time and expense.

Maintenance Impact

Maintenance of the sensors themselves is not generally reported to be a problem. Manufacturers offer sensors that recalibrate themselves automatically and that are guaranteed not to need calibration for up to 5 years. However, it is recommended that calibration be checked periodically by comparing sensor readings during a several-hour period when the building is unoccupied with readings from the outdoor air. Many sensor models are able to sense calibration problems and alert maintenance personnel if they are malfunctioning.

Costs

Costs for sensors have dropped by about 50% over the last several years. Sensors typically cost about \$250 to \$260 each, uninstalled. For a new system, the installed cost will generally be about \$600 to \$700 per zone. For a retrofit system, the cost will depend on what type of control system the building has. A controls contractor estimates installed costs for retrofit applications at from \$700 to \$900 per zone for systems with an existing DDC programmable controller and from \$900 to \$1200 per zone for systems with pneumatic, electronic, or application-specific DDCs. Installation costs for wireless systems are minimal beyond the cost of the actual sensor and gateway that can serve multiple sensor units.

In addition to the installation of the sensors, other components such as variable frequency drives and control input and output hardware often are needed to control the whole building, incrementally increasing the overall installed project cost beyond just the sensor installation cost.

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Abstract

Demand-controlled ventilation (DCV) using carbon dioxide (CO_2) sensors combines two technologies: advanced gas sensing and an air-handling system that uses data from the sensors to regulate ventilation. CO_2 sensors continually monitor the air in a conditioned space. Since people exhale CO_2, the difference between the indoor CO_2 concentration and the level outside the building indicates the occupancy and/or activity level in a space and thus its ventilation requirements. The sensors send CO_2 readings to the ventilation controls, which automatically increase ventilation when CO_2 concentrations in a zone rise above a specified level.

Either too little or too much fresh air in a building can be a problem. Overventilation results in higher energy usage and costs than are necessary with appropriate ventilation while potentially increasing IAQ problems in warm, humid climates. Inadequate ventilation leads to poor air quality that can cause occupant discomfort and health problems. To ensure adequate air quality in buildings, the American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE) recommended a ventilation rate of 15–20 cfm per person in ASHRAE Standard 62-1999. To meet the standard, many ventilation systems are designed to admit air at the maximum level whenever a building is occupied, as if every area were always at full occupancy. The result, in many cases, has been buildings that are highly overventilated. The development of CO_2-based DVC was driven in part by the need to satisfy ASHRAE 62 without overventilating.

Non-dispersive infrared CO_2 sensors are the type most widely used. All major makers of heating, ventilation, and air-conditioning (HVAC) equipment and HVAC controls offer the sensors, either as separate units or as a part of packaged HVAC systems. Although earlier sensors were plagued by reliability and calibration problems, those issues seem to have been largely resolved in newer models.

Typically, a CO_2 sensor is installed on the wall like a thermostat. Newer products entering the market combine thermostats and CO_2 and relative humidity sensors, the three primary indicators of human comfort, in one unit. Sensors may be installed inside ductwork rather than wall-mounted, but in-duct installation is not recommended for all applications. In a conventional “wired” CO_2 sensor system, wires are run from the sensors to the HVAC controls or to the damper actuators. With wireless CO_2 sensors, the data are transmitted to the building automation system via a wireless gateway for use in the control algorithm. Properly functioning modulating dampers are necessary. Pneumatic controls may need to be replaced with electronic or direct digital controls. In a retrofit installation, dampers may need to be repaired or upgraded to work with the sensors.

In all applications of CO_2-based DCV, a minimum base ventilation rate must be provided at all times the building is occupied. A higher rate may be needed for buildings in which building materials, contents, or processes release chemicals into the air. DCV should be used only in areas where human activity is the main reason for ventilating the space. Industrial or laboratory spaces are unsuitable for CO_2-based ventilation control.

The potential of CO_2-based DCV for energy savings is estimated at from $0.05 to more than $1 per square foot annually. The highest payback can be expected in high-density spaces in which occupancy is variable and unpredictable (e.g., auditoriums, some school buildings, meeting areas, and retail establishments), in locations with high heating and/or cooling demand, and in areas with high utility rates. Case studies show DCV offers greater savings for heating than for cooling. In areas where peak power demand and peak prices are an issue, DCV can be used to control loads in response to real-time prices. In those locations, DCV may enable significant cost savings even with little or no energy savings.

CO_2-based DCV does not interfere with economizers or other systems that introduce outdoor air into a building for cooling. Economizer operation overrides DCV when conditions warrant economizer use. Buildings that use evaporative cooling may not benefit from DCV during the cooling season.

Costs for sensors have dropped by about 50% over the last several years as the technology has matured and become more widely used. Sensors typically cost about $250 to $260 each, uninstalled. For a new system, the installed cost will generally be about $600 to $700 per zone. For a retrofit system, the cost will depend on what type of control system the building has and the degree of difficulty of installing signal and power wiring for a wired system. A complete wireless sensor system can be deployed quickly and without additional cost as such systems are battery powered. Given the advances in battery technology and microprocessor-controlled power management, sensors can be expected to operate for 2–3 years before they require a battery change.

About the Technology

Demand-controlled ventilation (DCV) using carbon dioxide (CO_2) sensing is a combination of two technologies: CO_2 sensors that monitor the levels of CO_2 in the air inside a building, and an air-handling system that uses data from the sensors to regulate the amount of outside air admitted for ventilation. DCV operates on the premise that basing the amount of ventilation air on the fluctuating needs of building occupants, rather than on a pre-set, fixed formula, will save energy and at the same time help maintain indoor air quality (IAQ) at healthy levels.

CO_2 sensors continually monitor the air in a conditioned space. Because people constantly exhale CO_2, the difference between the indoor CO_2 concentration and the level outside the building indicates the occupancy and/or activity level in a space and thus its ventilation requirements. (An indoor/

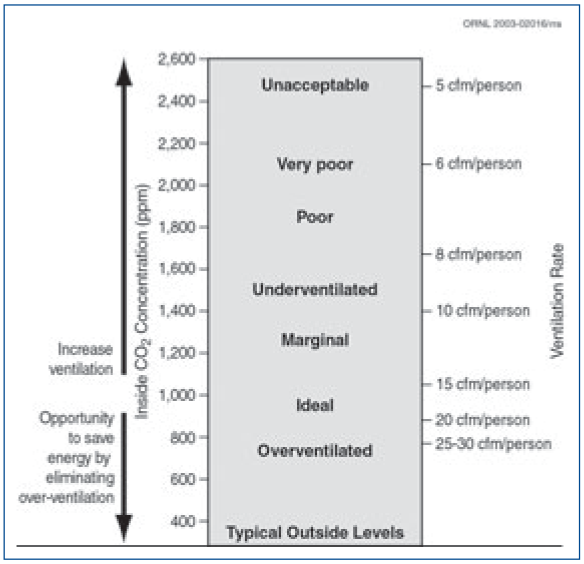


Figure 1. The relationship between CO_2 and ventilation rates, assuming office-type activity.

outdoor CO_2 differential of 700 ppm is usually assumed to indicate a ventilation rate of 15 cfm/person; a differential of 500 ppm, a 20 cfm/person ventilation rate, etc.) The sensors send CO_2 readings to the air handling system, which automatically increases ventilation when CO_2 concentrations in a zone rise above a specified level.

Building codes specify that a minimum amount of fresh air be brought into a building to provide for adequate air quality. The American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE) recommends a ventilation rate of 15-20 cfm per person in ASHRAE Standard 62.[1] To comply with codes, building ventilation systems often operate at constant or predetermined rates regardless of the occupancy level of the building. Many systems ventilate buildings at the maximum level all the time, as if every area were always fully occupied. Others are programmed to accommodate expected occupancy, varying the ventilation rate by time of day but without regard to the actual occupancy level. The result often is more ventilation air coming into buildings than is necessary. That air must be heated, cooled, or dehumidified/humidified, resulting in higher energy consumption and costs than would be necessary with appropriate ventilation. In addition, in humid climates, an overload of fresh air can result in uncomfortable humidity and mold and mildew growth, making the indoor air quality worse rather than better.

A lack of adequate fresh air, on the other hand, can make building occupants drowsy and uncomfortable as occupancy-related contaminants accumulate. A CO_2 level of around 1100 ppm (a differential of 700 ppm, assuming the outdoor air CO_2 level is around 400 ppm) indicates that the ventilation rate has dropped below acceptable levels and that contaminants in the air are increasing.

To avoid the problems of too much or too little fresh air, a heating, ventilation, and air-conditioning (HVAC) system can employ DCV to adjust the amount of ventilation air supplied to an indoor space according to the occupancy level. CO_2 sensors have emerged as the primary technology for monitoring occupancy and implementing DCV.

Application Domain

CO_2 sensors have been available for about 12 years. An estimated 60,000 CO_2 sensors are sold annually for ventilation control in buildings, and a manufacturer estimates the market is growing at about 40 to 60% per year. There is a potential for millions of sensors to be used, since any building that has fresh air ventilation requirements could potentially benefit from this refined control technology.

DCV using CO_2 sensors has the most energy-saving potential in buildings where occupancy fluctuates during a 24-hour period, is unpredictable, and peaks at a high level, for example, office buildings, government facilities, retail stores and shopping malls, movie theatres, auditoriums, schools, entertainment clubs and nightclubs. In buildings with more stable occupancy levels, DCV can ensure that the target ventilation rate per person is being provided at all times. DCV is more likely to reduce energy costs in areas with high utility rates or climate extremes.

CO_2-based DCV can operate in conjunction with economizers or other systems that introduce outdoor air into a building for heating or cooling. However, energy savings may be less where economizers are in use, depending on climate, occupancy schedule, and building type.

Buildings that use evaporative cooling may not benefit from DCV during the cooling season, and those that use heat exchangers to transfer heat between incoming and outgoing air may not realize significant energy savings.

In the next revision of its building code, California will begin requiring CO_2-based DCV in all buildings housing 25 people or more per 1000 ft^2. A proposed change in the Oregon building code would require DCV for HVAC systems with ventilation air requirements of at least 1500 cfm, serving areas with an occupant factor of 20 or less. ASHRAE 90 requires CO_2 sensors for DCV in high-density applications. The U.S. Green Building Code gives points in its Leadership in Energy and Environmental Design (LEED) rating system for use of CO_2-based ventilation control in buildings.

CO_2 sensors are considered a mature technology and are offered by all major HVAC equipment and controls companies. The technology is recognized in ASHRAE Standard 62, the International Mechanical Code (which establishes minimum regulations for mechanical systems), and some state and local building codes. The first CO_2 sensors sold were expensive, unreliable, and

[1] An ASHRAE standard is usually designated by a standard number and the year in which it was last revised. Standard 62 is under continuous maintenance and is constantly being revised.

difficult to keep calibrated accurately. However, manufacturers say they have largely resolved those problems-the units currently available generally are self-calibrating and similar to thermostats in price and reliability. A few years ago, sensors cost around $400 to $500 each; the cost now is usually about $200 to $250 per sensor (not including installation). As market penetration increases, sensor prices are expected to fall further.

Several manufacturers produce CO_2 sensors for use in DCV. Most manufacturers of thermostats and economizers are integrating CO_2 sensors into their products, and major manufacturers of packaged rooftop HVAC systems offer factory-installed CO_2 sensors as an option.

CO_2-based DCV is suitable only when there is a means of automatically adjusting the ventilation air supply (e.g., variable-speed fans or some variable damper arrangement). If this control is not presently available, the savings from DCV may justify the modifications to accommodate this degree of control.

CO_2 sensors designed for DCV are suitable only for controlling occupant-related ventilation. DCV does not eliminate the need for a base rate of ventilation to prevent degradation of air quality from contaminant sources unrelated to building occupancy, such as emissions from building materials. Thus CO_2-based DCV may not be appropriate—or may require higher target ventilation settings-in new buildings or others where there are contaminants not related to human occupancy, as it may not provide sufficient fresh air to dilute those contaminants. The CO_2 sensors used for DCV are not appropriate to monitor CO_2 for medical or industrial purposes that demand precise air quality control.

DCV should be used only in areas where human activity is the main reason for ventilating the space. Industrial or laboratory spaces that are subject to indoor air quality (IAQ) degradation from a wide variety of sources are unsuitable for CO_2-based ventilation control.

Energy-Saving Mechanism

The energy savings from CO_2 sensors for DCV result from the avoidance of heating, cooling, and dehumidifying fresh air in excess of what is needed to provide recommended ventilation rates. Many HVAC systems ventilate at a constant fixed level, usually the level prescribed for full occupancy, and thus provide more fresh air per occupant than the designed ventilation rate much of the time. Moreover, systems using fixed ventilation rates cannot accurately account for unanticipated air infiltration into a building (e.g., from leakage or opened windows) and adjust the fresh air intake accordingly.

DCV based on CO_2 sensing allows real-time control of the ventilation levels according to building occupancy. If a building is only 50% full, then only 50% of the design-rate ventilation air, not 100%, is pulled in. CO_2 sensors are the most widely accepted technology currently available for implementing DCV. They do this by increasing the ventilation rate whenever the CO_2 level in a space reaches a predetermined level that represents a differential between the indoor and outdoor CO_2 levels. The outdoor CO_2 level is slightly dependent on local conditions and elevation, but can generally be assumed to be around 400 ppm. An indoor level of 1100 ppm of CO_2 thus represents a 700-ppm differential and indicates a ventilation rate of 15 cfm per person in the occupied space. A differential of 500 ppm in the same space would indicate a ventilation rate of 20 cfm per person.

The technology most often used in CO_2 sensors is non-dispersive infrared spectroscopy. It is based on the principle that every gas absorbs light at specific wavelengths. Carbon dioxide sensors calculate CO_2 concentrations by measuring the absorption of infrared light (at a wavelength of 4.26 microns) by CO_2 molecules. The sensor apparatus incorporates a source of infrared radiation, a detector, and electronics to detect the absorption. Air from the area being monitored diffuses into a chamber

Figure 2. Typical non-dispersive infrared spectroscopic CO_2 sensor.

that has a light source at one end and a light detector at the other. Selective optical fibers mounted over the light detector permit only light at the 4.26-micron wavelength absorbed by CO_2 to pass through to the detector. As CO_2 levels rise, more infrared light is absorbed and less light is detectable.

Photo-acoustic CO_2 sensors also are available. In these sensors, also, air diffuses into a chamber in the sensors and is exposed to light at the wavelength absorbed by CO_2. As the CO_2 molecules absorb light energy, they heat the air chamber and causes pressure pulses. A piezo-resistor senses the pulses and transmits data to a processor that calculates the CO_2 level.

Electrochemical sensors measure the current transmitted across a gap filled with an electrochemical solution. CO_2 decreases the pH of the solution, freeing conductive metal ions. A weak electrical current can then flow across the gap; the current signals an increase in the CO_2 level.

Mixed-gas sensors also can detect CO_2 along with other gases in the air, but they have not proved to be effective for DCV because they do not measure CO_2 specifically and cannot be tied to ventilation rates as explicitly as a CO_2 sensor can.

Sensors generally are either wall-mounted in the space to be monitored or mounted inside the duct system. (Wall-mounted sensors usually are recommended because duct-mounted units provide data on the average CO_2 concentration in multiple spaces rather than on the CO_2 levels in individual areas.)

The sensors monitor CO_2 concentrations continually and send data to the system for controlling the ventilation equipment. Various types of control systems can be used to incorporate CO_2 sensing: simple setpoint control that activates a fan or damper when CO_2 levels exceed a setpoint; proportional control, in which sensor data adjust ventilation air volume through a range of levels; proportional-integral control, in which fresh air intake is controlled not only by the CO_2 level but also by the rate at which the level is changing; and two-stage controls for zone-based systems in which both temperature sensors and CO_2 sensors control ventilation.

Other Benefits

Potential secondary benefits of CO_2-based DCV include:

- Improved IAQ: By increasing the supply of fresh air to the building if CO_2 levels rise to an unacceptable level, the technology could prevent under-ventilation that results in poor air quality and stuffy rooms.
- Improved humidity control: In humid climates, DCV can prevent unnecessary influxes of humid outdoor air that causes occupants to be uncomfortable and encourages the growth of mold and mildew.
- Records of air quality data: Sensor readings can be logged to provide a reliable record of proper ventilation in a building. Such records can be useful in protecting building owners against ventilation-related illness or damage claims.
- Reduced operational running times for the major HVAC equipment: Improving the ability to condition the building could delay start-times of the HVAC equipment during morning pre-conditioning periods by as much as several hours on a Monday morning in humid climates, resulting in incremental energy and cost savings.

Variations

DCV can be implemented using methods other than CO_2 sensing to indicate occupancy levels or air quality conditions. For example, humidity sensors, motion detectors, particle counters, volatile organic contaminant sensors, and mixed-gas sensors can be used to regulate DCV. Time-controlled ventilation (e.g., using programmed time clocks) is also an option for buildings that are occupied only during certain times, for example, office buildings and schools. Based on a review of the literature, it appears that CO_2 sensors are becoming the industry standard for typical DCV applications.

CO_2 sensors are of three main types: infrared, electrochemical, and photo-acoustic. Based on the literature, infrared sensors appear to be the type most commonly used for DCV applications.

Combination sensing units are available that package wall-mounted CO_2 sensors with thermostats or with humidity sensors.

There are numerous variations in the types of HVAC systems and control systems with which CO_2-based DCV is implemented. CO_2-based DCV capability can be added to an existing system by installing sensors and connecting them with the air handling systems. Increasingly, new HVAC systems are being factory-equipped with input and controls strategies to accept CO_2-based DCV.

Installation

Typically, a CO_2 sensor is installed on the wall like a thermostat. Newer products entering the market combine thermostats and CO_2 and relative humidity sensors, the three primary indicators of human comfort, in one unit. Sensors may be installed inside ductwork instead of on a wall, but in-duct installation is not recommended for applications where the sensor would

All of these types of systems can be modified to accomplish a DCV strategy

Control Type	Minimum Modification	Recommended Modification
All	Apply ASHRAE Standard 62-1999 with CO_2 sensors provided in zones with high critical outside air (OA) calculations	Provide CO_2 sensors in all zones, using the highest zone to increase the fresh air provided by the associated air-handling unit (AHU)
Pneumatic	Provide electronic-to-pneumatic transducer to limit the OA damper position	Upgrade the AHU to DDC programmable control
Electronic	Provide electronic device to limit the OA damper position	Upgrade the AHU to DDC programmable control
DDC–application specific	Provide electronic device to limit the OA damper position	Upgrade the AHU to DDC programmable control
DDC-programmable	Modify the control program to provide new DCV strategy	Same as minimum

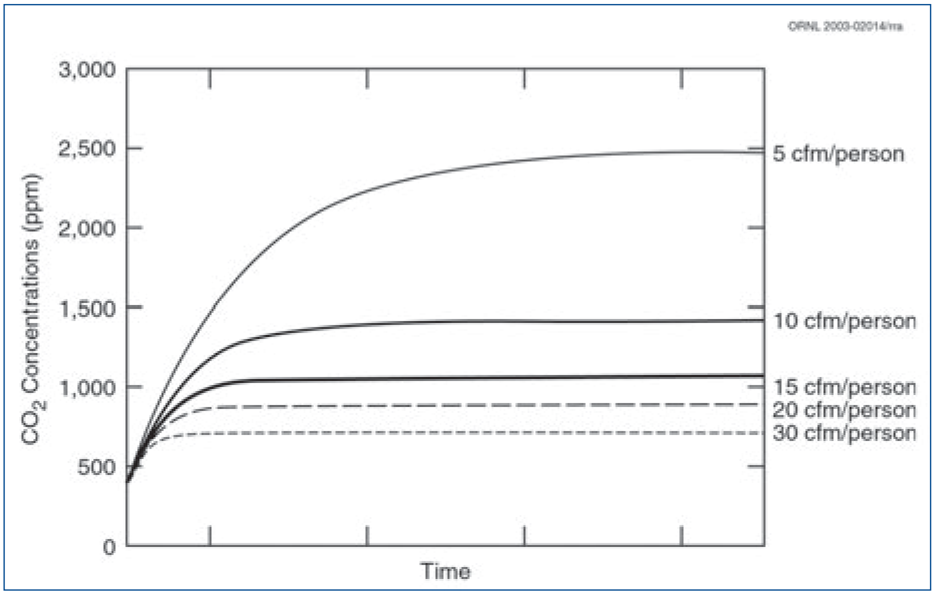


Figure 3. CO_2 equilibrium levels at various ventilation rates.

average readings from several different areas. With hardwired sensors (those requiring both power and signal wiring), wires are run from the sensors to the building's HVAC control system or to the actuator that controls the fresh air supply. Wireless sensors require neither power nor signal wiring, and the sensor data are fed into the HVAC controls via a gateway using one of several communication protocols.

In a building retrofit, dampers may need to be repaired or upgraded to work with the sensors. Properly functioning modulating dampers are necessary. Pneumatic controls will need to be replaced with electronic or direct digital controls (DDCs); it may also be worthwhile to replace existing electronic controls with DDCs. Actuator modules that do not have input points for the sensors will need to be upgraded.

Part of the preparation for implementing DCV is to monitor the air in the outdoor areas surrounding the building for at least a week to establish the CO_2 concentration in the ventilation air. The differential between the CO_2 levels of the outdoor and indoor air will determine the amount of fresh air needed to meet ventilation requirements. CO_2 concentrations in all zones inside the conditioned space also should be monitored for several days to indicate existing ventilation levels in the zones. This monitoring may identify problems with air-handling systems that need to be corrected before DCV is implemented.

To ensure that the sensors are correctly calibrated and working properly, a hand-held monitor should be used to check CO_2 concentrations inside the buildings regularly for a few days after the system begins operating. The readings from the monitor should be compared with the readings the sensors are sending to the ventilation system controls. Sensors that prove to be improperly calibrated should be recalibrated.

In all applications of CO_2-based DCV, a minimum ventilation rate should be provided at all times the building is occupied. A rate of 20–30% of the original design ventilation rate for the space at maximum occupancy is often recommended as a new baseline ventilation rate. A higher rate may be needed for buildings in which building materials, contents, or processes release chemicals into the air.

Federal-Sector Potential

Federal Technology Alerts target technologies that appear to have significant untapped federal-sector potential and for which some installation experience exists. CO_2 sensors are recognized as having potential to reduce energy consumption and costs resulting from over-ventilation of buildings while guarding against under-ventilation.

Estimated Savings and Market Potential

CO_2-sensors for demand-controlled ventilation are recognized as having potential to reduce energy consumption, costs, and emissions.

Demand-controlled ventilation has not been assessed by the New Technology Demonstration activities. There are no known estimates of the savings potential of CO_2-based DCV for the federal building sector. Therefore, this report cannot adequately quantify the energy-savings potential of the application of this technology for the federal sector.

The literature about DCV includes numerous estimates and models of the savings potential of DCV, as well as accounts of monitored savings in specific applications. The predicted and actual savings vary widely depending on climate, type of HVAC system with which DCV is implemented, occupancy patterns in the space in which is it implemented, and other operating conditions. The capability of the building staff to keep equipment adequately maintained and operating properly also may affect savings significantly.

The potential of CO_2-based DCV for operational energy savings has been estimated in some of the literature at from $0.05 to more than $1 per square foot annually. The highest payback can be expected in high-density spaces in which occupancy is variable and unpredictable (e.g., auditoriums, some school buildings, meeting areas, and retail establishments), in locations with high heating and/or cooling demand, and in areas with high utility rates.

A report by Lawrence Berkeley National Laboratory cited five case studies in large office buildings with CO_2-based DCV, all of which reported energy savings that resulted in payback times of from 0.4 to 2.2 years. Two of the studies were computer simulations. One of those, conducted in 1994, simulated a 10-floor office building located in Miami, Atlanta, Washington, D.C., New York, and Chicago. The simulation predicted large gas savings for heating and smaller electricity savings, resulting in predicted payback times for the different locations of from 1.4 to 2.2 years.

A 1999 study modeled the impact of DCV and economizer operation on energy use in four building types (office, retail, restaurant, school) in three locations representing different climates: Atlanta; Madison, Wisconsin; and Albuquerque. For cooling, predicted savings attributed to DCV depended greatly on location-savings were larger in Atlanta and Madison because humidity made economizer operation less beneficial. In low-humidity Albuquerque, economizer operation was much more significant than DCV in reducing cooling energy demand. In all three locations, DCV resulted in large savings in heating energy—27%, 38%, and 42% for the office building in Madison, Albuquerque, and Atlanta, respectively; from 70% in Madison to over 80% in Atlanta and Albuquerque for the school; and over 90% in all three locations for the retail and restaurant spaces. Similar results were obtained for 17 other U.S. locations modeled. In all locations, the office building showed the most modest savings.

A recent proposal for a change to the Oregon building code to require DCV in some applications cites a DOE2 analysis of implementing a DCV strategy in a middle school gymnasium. It predicts energy cost savings of $3700 per year from DCV and a simple payback of about 6 months.

No estimate of market potential for CO_2-based DCV in the federal sector was available.

Laboratory Perspective

Research on CO_2-based DCV at the national laboratories has been limited so far. The technology is generally regarded as a valid operational strategy that offers potential for energy and cost savings and protection of IAQ in many facilities. A study conducted by Lawrence Berkeley National Laboratory concludes that sensor-regulated DCV is generally cost-effective in buildings in which the measured parameter (e.g., CO_2) is the dominant emission, the occupancy schedule and levels are varied and unpredictable, and the heating/cooling requirements are large. Monitoring of CO_2-based DCV systems is under way at some national laboratories to quantify savings and analyze effects on IAQ.

Some caveats have emerged from laboratory experience. Calibration drift has been observed to be a problem in some sensors. The management of energy management systems so that they admit ventilation air at an appropriate CO_2 level is another. A researcher at Oak Ridge National Laboratory who works with building projects at federal facilities noted that a skilled, well-trained building maintenance staff is essential to proper functioning of the sensors and associated control systems. If other HVAC control systems in a building frequently function improperly, there probably will be problems with CO_2 sensors and DCV controls, also. He advises that a test installation be tried first to ensure that the building staff understand how the devices work, that the devices function properly, and that the staff can handle a larger DCV implementation.

Application

This section addresses technical aspects of applying the technology. The range of applications and climates in which the technology can be best applied are addressed. The advantages, limitations, and benefits in each application are enumerated. Design and integration concerns for the technology are discussed, including equipment and installation costs, installation details, maintenance impacts, and relevant codes and standards. Utility incentives and support are also discussed.

Application Screening

DCV based on CO_2 sensing offers the most potential energy savings in buildings where occupancy fluctuates during a 24-hour period, is somewhat unpredictable, and peaks at a high level. It is also more likely to reduce energy costs in locales that require heating and cooling for most of the year and where utility rates are high.

Savings opportunities are the greatest in buildings with low average occupancy levels compared with the design occupancy levels. Larger savings are likely in buildings that supply 100% outside air to conditioned spaces than in buildings that supply a mixture of outside and recirculated air.

Types of buildings in which CO_2-based DCV is likely to be cost-effective include large office buildings; assembly rooms, auditoriums, and lecture halls; large retail buildings and shopping malls; movie theaters; restaurants, bars and nightclubs; banks; outpatient areas in hospital; and hotel atriums or lobbies.

In primary and secondary schools, where occupancy is variable but predictable, time-controlled DCV may be more

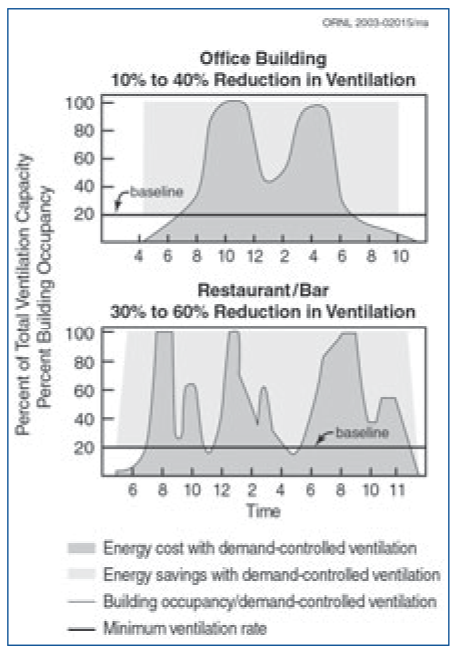


Figure 4. Percent of total ventilation capacity percent building occupancy.

cost-effective. College classroom buildings and large lecture rooms with variable occupancy through the day and the week are more appropriate candidates.

CO_2-based DCV does not interfere with economizers or other systems that introduce outdoor air into a building for cooling. Economizer operation overrides DCV when conditions warrant economizer use. The energy and cost savings for such arrangements depend on climate, occupancy schedule, and building type. Warm, humid climates (e.g., the Southeast) offer the most potential to save cooling energy with DCV because high humidity reduces opportunities for economizer cooling. In dry climates such as the desert Southwest, economizer operation may save more cooling energy than DCV. Additional cooling savings from DCV may be insignificant in such climates, and DCV without economizer cooling may even result in an energy penalty.

Buildings that use evaporative cooling may not benefit from DCV during the cooling season.

Case studies generally show greater savings for heating than for cooling in all climates. Heating savings are greatest where heating the ventilation air accounts for a large portion of the energy demand. A building with exchangers to transfer heat between incoming and exhaust air has less potential for savings from DCV because the heat exchangers reduce the energy penalty of ventilation air.

In areas where peak power demand and peak prices are an issue, DCV can be used to control loads in response to real-time prices. In those locations, DCV may enable significant cost savings even with little or no energy savings.

DCV can be implemented only in buildings in which the outside air supply can be automatically adjusted. If the air-handling system lacks that capability, it must be upgraded before CO_2-based DCV can be implemented. It is recommended that pneumatic controls be replaced with electronic or digital controls to implement CO_2-based DCV.

The cost of installing CO_2 sensors for DCV depends on how easily the existing control system can incorporate them. If the existing system has digital controls and available input points on the control modules for wired sensors, costs will be lower and implementation easier. Wireless sensors may be more easily integrated into an existing control system, as no new input control modules are needed.

Modeling is recommended, if feasible, to estimate the energy savings and cost-effectiveness of DCV in a specific situation.

CO_2 from human respiration must be the dominant pollutant in a space for CO_2-based DCV to be appropriate. Otherwise, it could lead to insufficient ventilation. Occupancy-based DCV is inappropriate for spaces with high levels of contaminants unrelated to human occupancy, including industrial or laboratory spaces. If CO_2-based DCV is used in a new building or other space containing materials that release irritating emissions (e.g., a clothing or carpet store), the target ventilation rate must be high enough to ensure that emissions are adequately diluted.

An HVAC system with CO_2-based DCV needs to be capable of a daily pre-occupancy (e.g., early morning) purge of inside air to avoid exposing occupants to emissions (e.g., from building materials) that accumulate while ventilation is at a low level.

Although DCV was developed mainly as an energy-efficiency technology, it also is useful to ensure acceptable IAQ. In a properly operating system, CO_2-based DCV ensures that the target ventilation rate per person is being provided at all times. Thus it may be appropriate for spaces where there are IAQ concerns. It may also help control the growth of mold and mildew by reducing unnecessarily large influxes of humid outdoor air.

Where to Apply

- Buildings where occupancy fluctuates during a 24-hour period, is somewhat unpredictable, and peaks at a high level.
- Locales that require heating and cooling for most of the year.
- Areas where utility rates are high.
- Areas where peak power demand and prices are high.
- Buildings with low average occupancy compared with the design occupancy.
- Large office buildings; assembly rooms, auditoriums, and lecture halls; large retail buildings and shopping malls; movie theaters; restaurants, bars and nightclubs; banks; outpatient areas in hospital; and hotel atriums or lobbies.
- Warm, humid climates.
- Buildings in which heating/cooling/dehumidifying the ventilation air accounts for a large portion of the energy demand.
- Buildings in which the outside air supply can be automatically adjusted.
- Buildings with HVAC systems that have, or can be upgraded to, electronic or digital controls.
- Spaces in which CO_2 from human respiration is the only or dominant pollutant.
- Spaces that do not have high levels of contaminants unrelated to human occupancy (e.g., industrial or laboratory spaces).
- Buildings in which poor IAQ resulting from under-ventilation or excessive humidity resulting from under- or over-ventilation is a concern.

Precautions

The following precautions should be kept in mind in considering the use of CO_2-based DCV.

- Sensors should be placed where they will provide readings that are close to actual conditions in the spaced to be controlled.
- Wall-mounted sensors are generally preferable to duct-mounted sensors.

- Sensors should not be mounted in locations where people will regularly breathe directly on them (e.g., at standing level near the coffee machine).
- Don't buy carelessly—choose sensors with a reputation for performing well in terms of self-calibration, drift, accuracy, and reliability.
- A competent, well-trained maintenance staff is important to a successful implementation.
- In a retrofit, it is important to make a thorough study of the HVAC system and troubleshoot for existing ventilation problems before installing a DCV system.
- A new base ventilation rate should be provided at any time the building is occupied. An often-cited guideline is 20 to 30% of the original design rate.
- Applications in moderate climates, especially where economizer operation contributes substantially to cooling, may show little energy/cost savings.
- Spaces where there are high levels of contaminants not related to occupancy may demand a higher ventilation rate than would be provided by DCV based solely on CO_2 levels.
- During the first year or so in a new building, it is advisable to maintain a higher ventilation rate than CO_2 sensing would indicate to ensure proper dilution of emissions from new materials.

Design Considerations

CO_2 sensing is a fairly simple technology, and installation of the sensors themselves is not complicated. Sensor voltage, power, and control output requirements are similar to those used commonly by thermostats. For wired sensor installations, the type of wire used for the signal wiring is often critical; some controls manufacturers specify the wire gauge, type, and shielding/grounding requirements to prevent signal irregularities and errors. With wireless sensors, these considerations are not a concern, as data are transmitted over a Federal Communications Commission-approved frequency. The wireless sensors are self-powered and use on-board power management to alert the building operator when the battery needs to be changed.

Most HVAC equipment suppliers are now offering systems designed to accommodate DCV and accept readings from CO_2 sensors, so including CO_2-based DCV in a new HVAC installation should not add significantly to the difficulty of getting the system into operation. However, retrofitting an existing system to work with DCV may be more problematic, particularly for an older system with pneumatic controls.

The sensors typically are mounted on walls like thermostats. Some manufacturers offer thermostat/sensor combinations. Units that monitor temperature, CO_2, and humidity are also available; they are useful with systems that include desiccant dehumidification to control the humidity load in ventilation air.

Data from the sensors are fed to the building's HVAC control system or to an actuator that controls the amount of ventilation air that is admitted. In a retrofit installation, it may be necessary to repair or upgrade dampers so they will work in a more dynamic, modulating fashion in response to the sensors. Properly functioning dampers that can be automatically controlled are essential. Pneumatic controls will need to be replaced with electronic controls or DDCs; it may also be worthwhile to replace existing electronic controls with DDCs. Actuator modules that do not have input points for the sensors will need to be upgraded to add input points.

Air handler unit and variable-air-volume controls are used for communication between the sensors and the air-handling system.

Control Type	Control Medium	Sequence
Pneumatic	Air pressure from 3 to 15 psi	Hard-piped: changes require additional hardware and physical modifications to the control air tubing
Electronic	Electronic signals from 2 to 10 V DC, 0 to 10 V DC, 4 to 20 mA are the most common. Other signals are 3 to 9 V DC, 6 to 9 V DC, 0 to 20 V phase cut	Hard-wired: changes require additional hardware and physical modifications to the control wiring
Direct digital control (DDC)—application-specific	Electronic signals from 2 to 10 V DC, 0 to 10 V DC, 4 to 20 mA are the most common. Other signals are 3 to 9 V DC, 6 to 9 V DC, 0 to 20 V phase cut, and via wireless transmission to multi-protocol enabled gateways	Programmed into an electronic controller that can be configured: some systems may need additional hardware to accomplish desired sequences
DDC—programmable	Electronic signals from 2 to 10 V DC, 0 to 10 V DC, 4 to 20 mA are the most common. Other signals are 3 to 9 V DC, 6 to 9 V DC, 0 to 20 V phase cut and via wireless transmission to multi-protocol enabled gateways	Programmed into an electronic controller that can be reprogrammed to accomplish desired sequences

The application of a CO_2-based DCV strategy using ASHRAE 62 is more complicated than simply installing CO_2 sensors and using them to control dampers. In variable-air-volume systems, particularly, fairly complex calculations and control algorithms may be necessary to program the control system properly for DCV.

DCV is compatible with economizers or other systems that can bring outdoor air into a building for cooling. Economizer operation overrides DCV when conditions favor economizer use. DCV used in conjunction with an enthalpy economizer (one regulated by relative humidity) probably will save more energy than DCV with a temperature-regulated economizer.

Heat exchangers that transfer heat between supply air and exhaust air reduce the energy demand caused by large inflows of ventilation air; therefore, DCV may not reduce energy use in buildings with heat exchangers. Evaporative cooling systems may not benefit from DCV during the cooling season.

Maintenance Impact

Maintenance of the sensors themselves is not reported to be a problem. Although earlier sensor models had reliability problems, the literature generally reports that newer models typically are reliable and accurate. Manufacturers offer sensors that recalibrate themselves automatically and that are guaranteed not to need calibration for up to 5 years. However, it is recommended that calibration be checked periodically by comparing sensor readings during a several-hour period when the building is unoccupied with readings from the outdoor air. Many sensor models are able to sense calibration problems and alert maintenance personnel if they are malfunctioning.

Some users report problems in getting the sensors calibrated initially. A hand-held monitor should be used to ensure that the installed sensors are measuring CO_2 concentrations in their zones accurately.

CO_2-based DCV is a more sophisticated technology than many maintenance personnel are accustomed to, a building researcher noted. A facility with a well-trained staff who know how to maintain and troubleshoot controls is the best candidate for a CO_2-based DCV system.

Equipment Warranties

The prospective user should ask potential suppliers, contractors, and installers about warranties for specific equipment models. Warranties for CO_2 sensors vary widely among different manufacturers. Those reviewed offer warranty periods for parts and labor ranging from 90 days from the date of shipment to 5 years from the date of purchase. A warranty period of 12 to 18 months for parts and labor appears to be fairly common. Some sensors are guaranteed to remain calibrated for at least 5 years, and at least one manufacturer offers a lifetime calibration guarantee.

Codes and Standards

The use of CO_2-based DCV is accepted in both ASHRAE 62 and the International Mechanical Code (IMC). The IMC is referenced by the Building Officials and Code Administrators International, the Southern Building Code Congress International, and the International Code Conference of Building Officials, which together establish the model code language used in local and state building codes through the United States. The commentary on IMC Section 403.1 states, "The intent of this section is to allow the rate of ventilation to modulate in proportion to the number of occupants. CO_2 detectors can be used to sense the level of CO_2 concentrations which are indicative of the number of occupants... and this knowledge can be used to estimate the occupant load in a space."

ASHRAE 62 recommends DCV for all ventilation systems with design outside air capacities of greater than 3000 ft^3 per inch serving areas with an average design occupancy density of more than 100 people per 1000 ft^2.

The California Building Standards Code was amended in June 2001 to require CO_2-based DCV in some high-density applications during periods of partial occupancy. A proposed change to the Oregon Building Code (NR-HVAC-7) would require HVAC systems to include provision for DCV during periods when spaces are only partially occupied.

Costs

Costs for sensors have dropped by about 50% over the last several years as the technology has matured and become more widely used. Sensors typically cost about $250 to $260 each, uninstalled. For a new system, the installed cost will generally be about $600 to $700 per zone. For a retrofit system, the cost will depend on what type of control system the building has. A controls contractor estimates installed costs for retrofit applications at from $700 to $900 per zone for systems with an existing DDC programmable controller and from $900 to $1200 per zone for systems with pneumatic, electronic, or application-specific DDCs. Installation costs for wireless systems are minimal beyond the cost of the actual sensor and gateway that can serve multiple sensor units.

In addition to the installation of the sensors, other components such as variable frequency drives, control input and output hardware are often needed to control the whole building, incrementally increasing the overall installed project cost beyond just the sensor cost.

Utility Incentives and Support

No specific information was found regarding utility incentives that are in place for CO_2-based DCV. Some states (e.g., California) are considering such an incentive program. Most electric and natural gas utility companies have rebate programs to promote energy-efficiency technologies that result in overall improvement in building performance, and DCV systems would quality for incentives under some of those programs.

DCV is one of the technologies that utilities might consider for financial incentives in working with federal customers through a utility energy service contract on energy-efficiency projects at federal sites.

Technology Performance

Field Experience

Three building operators whose facilities have installed CO_2 sensors for DCV and a controls engineer whose company oversees HVAC installations were contacted for this report regarding their experience with the use of CO_2-based DCV. All were generally pleased with the performance they have observed, although one reported problems with getting the sensors properly calibrated and wired.

Purdue University has installed CO_2 sensors in 12 large auditoriums and lecture halls (100 to 500 seats) to address both air quality issues and energy costs. The sensors were added to existing air handling systems, and modulating outside damper actuators were added where they were not already in place. The existing air-handling units were 15 to 50 years old. Some of the rooms had pneumatic dampers with electronic controls; those controls were not replaced unless they were in bad condition. The large auditoriums had DDC systems. All the existing control modules had enough available inputs to add the sensors.

Purdue's controls systems engineer reported that there were minor problems with retrofitting the older air-handling systems, but they were the same kinds of problems that would have surfaced with a conventional HVAC retrofit-a lack of original or updated building plans and plans that did not match the existing systems. "We had to do some legwork to verify the existing configurations. It would be easier with new systems," she said.

Purdue has found the equipment installed to be reliable, and it has performed as expected. There has been a negligible impact on the maintenance staff because the sensors installed recalibrate themselves automatically. Purdue had previously installed sensors from another manufacturer that proved unsatisfactory because they could not be calibrated properly or could not maintain their calibration, the controls engineer said. "The calibration issue is very important in sensor selection," she said. The maintenance for the other equipment installed has been comparable to maintenance on the systems replaced.

Once the sensors began operating, they revealed that some of the lecture rooms had been underventilated by the old systems. The sensors worked well in resolving IAQ issues. Purdue has not monitored energy use since the sensors and new dampers were installed, but trended data have shown that the ventilation dampers modulate to lower or minimal positions when the lecture rooms are unoccupied or partly occupied and on weekends. Before the sensors were installed, the dampers were open to ventilate for full occupancy during the occupied cycle time (6 A.M. to 10 P.M. weekdays and 8 A.M. to 4 P.M. Saturdays).

Purdue continues to install CO_2-based DCV in new applications in large rooms with variable occupancy. It will be added in a renovation of the air handling system in a 900-person-capacity ballroom of the Purdue Memorial Union and is being reviewed for application in dining halls on campus.

A CO_2 sensor was installed in an office building on the Beaufort Marine Corps Air Station in South Carolina to regulate the makeup air system. It is the first of several DCV retrofits planned on the base as part of an energy services performance contract and a Marine Corps-funded controls system upgrade for the station. The air station is located in the low country of South Carolina, a particularly humid climate with a heavy cooling load.

The office building, a one-story 41,354 ft^2 facility with no windows, contains offices and a flight simulator. It was designed for 500 people, and the ventilation system supplied enough air to meet ASHRAE standards for 500, but the occupancy is rarely over 100, said Neil Tisdale, utilities director for the base. "That's a lot of air to be conditioning for no reason." The sensor was added as part of a makeup-air-system retrofit. The system already had modulating dampers and DDCs. Adding CO_2-based DCV was fairly simple—installing a sensor and modifying the control program to regulate the damper with input from the sensor. The CO_2 sensor was placed in the return air path.

The system has been operating for a year, Tisdale said, and he is not aware of any maintenance problems or malfunctions. He ventured a rough estimate that the DCV system reduces the cooling load for the building by 20 tons, saving roughly of 12 megawatt hours of power annually. The load for the building's chiller, sized to provide cool air for 500 people, was reduced so much that part of the chilled water was diverted and used to cool an adjacent 11,000 ft^2 building.

A large hospital in Houston, Texas, has installed CO_2 sensors in its auditoriums to ensure good IAQ and control energy costs, according to the hospital's manager of energy services. The sensors were added to existing systems, all of which had digital controls; integrating the sensors was not difficult, he said. The sensor input is not yet being used to control the dampers automatically; building staff are monitoring the sensors to see whether they will control air changes properly before switching to automatic control. "We're going to take it a step at a time and expand gradually," the energy services manager said. The switch to direct control of dampers by the sensors will take "minutes" to implement and will probably occur during the coming year, he said.

When the hospital begin installing the sensors, it was discovered that about half of them were not wired properly and needed to be rewired, he said. Many of the units were calibrated incorrectly and had to be recalibrated using a hand-held meter. “Some of them were showing 4000 to 5000 ppm of CO_2. You can’t just set them up and assume they’ll work properly,” he cautioned.

However, he expects the sensors and DCV to perform well now that the initial problems have been addressed. They may be added in other areas such as busy foyers and other gathering areas once the conference room installation is in full operation.

The owner of a digital controls company who oversees HVAC installations says his company’s clients who have installed CO_2-based DCV systems have been generally pleased with their performance and found DCV to be a valuable addition. A new HVAC installation that incorporates CO_2 sensors and DCV is of minimal cost and difficulty and requires only a few additional calculations to set up the air handling program properly, he said. He cautions that sensors should be installed to cover every CO_2 zone in an area because high occupancy, and a corresponding high CO_2 level, in one zone may not be reflected in the sensor readings from the adjacent zone.

Although his firm has not done formal studies of savings from DCV, it has seen a reduction in outside air requirements in all DCV installations because none of the facilities are at the design occupancy all the time. The largest energy savings are likely in buildings designed to meet ASHRAE 62 requirements, he said, because they are likely to be admitting more unneeded outside air.

He notes that if a building has previously been chronically under-ventilated, installing DCV might increase rather than decrease energy usage because it would bring in more outside air. However, DCV will correct IAQ problems and reduce liability for IAQ-related illnesses in such situations and may correct problems with mold growth.

The maintenance impact of installing CO_2 sensors is usually minimal if the sensors are self-calibrating, he said. Sensor calibration can be checked periodically by comparing indoor sensor readings with metered outside air readings after a building has been unoccupied for about 5 hours.

Energy Savings

None of the building operators interviewed had measured energy consumption before and after the installation of CO_2 sensors. However, both Purdue staff and the controls company owner have observed lower outside air requirements in facilities using DCV, which generally results in reduced energy demand.

Maintenance Impact

The maintenance impact of installing CO_2 sensors has been minimal at Purdue. The sensors used are self-calibrating and have performed reliably. The hospital in Texas reported problems with getting several of the sensors calibrated initially and had to use hand-held monitors to recalibrate them. In addition, some of the sensors were wired improperly and had to be corrected.

Case Study

This case study describes the methodology used to assess the cost and energy savings implications of retrofitting a building for CO_2-based ventilation control. This methodology can be applied to any building that has a track record of energy usage. In this case, the preliminary assessment of the building showed significant energy savings were available. The performance of the building after 6 months of operating with CO_2 control is also presented and shows that the predicted performance was slightly conservative compared with the actual savings realized.

Facility Description

This case study addresses a privately owned (non-government) 30-story Class A office building in Birmingham that was retrofitted with a CO_2-based ventilation control system in 2001. It had an existing state-of-the-art digital building control system installed several years earlier that was fully functional. The building was also upgraded to qualify for the EnergyStar label awarded by EPA to buildings having met qualifying energy efficiency standards.

Utility costs for the building were very low, $0.48/kWh during the base year of 1999; overall energy costs for the base year were $1.61 ft^2/year, representing 117,992 Btu/ft^2/year. This energy performance was compared with that of other similar buildings in that region using the DOE Energy Information Administration (EIA) energy intensity indices, which provide a general guide to average energy usage for different types of buildings in a region. The case study building was found to consume about 30% more than those found in the EIA indices. The fact that the energy cost was higher than average provided some preliminary indication that despite the low utility costs and EnergyStar rating, there were some opportunities for further energy conservation.

Of the total energy consumed by the building in the year 2000, 84.55% was spent on electricity for a total of 13,966,500 kWh or $670,742 annually; the maximum peak load was 3,318 kW. Of the remaining total energy consumed by the building, 13.81% was spent on steam for a total of 7,810,000 lb at a cost of $122,581 annually.

Existing Technology Description

The building HVAC system was designed with two air-handling units (AHUs) per floor, located on opposite sides of the building. Variable air volume (VAV) boxes served interior zones, and linear diffusers were located on perimeter zones. The linear diffusers have re-heat capability; the interior VAV boxes do not. Each AHU fan motor was controlled by a variable-frequency drive (VFD) to supply VAV boxes on the floor. Each AHU was on a time-of-day schedule provided by the automation system, wherein the units were scheduled on and off to correspond with the staff occupancy for that particular floor on a Monday through Friday basis, with limited Saturday hours of operation. Sunday was most often scheduled off all day for most floors. Because of the nature of the client operations, a few floors operated 24 hours per day, 7 days per week.

Outside air is drawn into each AHU at each floor through a ducted grille. The combined general building and bathroom exhaust are provided by twin fans (of differing sizes) exhausted at the roof level by connecting all floors through twin vertical shafts. Both exhaust fans were of a constant-speed design, exhausting the full design load air regardless of the intake of outside air into the building. Although a limited number of floors operated 24 hours per day, both exhaust fans ran constantly at the full design load. This feature probably also contributed to the higher than normal operating cost for the building.

The building had a DDC building air system that was deemed capable of executing a DCV strategy with some additional programming, and had sufficient input/output capacity to add the required components (e.g., CO_2 sensors, peripheral I/O modules).

New Technology Equipment Selection

The building automation system (BAS), an existing Siemens System 600, had been installed several years previously. It was deemed capable of accepting the data from the new CO_2 sensors, able to execute the new control strategy, and to have sufficient spare point capacity to provide the required input/output (I/O) from/to the new devices. Four new Telaire series 8002, dual-beam CO_2 sensors were installed per floor, except on the second floor, which had a number of enclosed meeting/conference rooms. One CO_2 sensor was installed in each of these rooms. One outside CO_2 sensor was installed to provide accurate indoor/outdoor CO_2 differential readings.To facilitate the additional I/O point requirements, new modules were installed within each S600 cabinet. For the CO_2 sensors, analog input modules accepting a 4-20 mA signal were needed, for the new fully proportional electric actuators, replacing the old relay (open/closed) actuators required analog modules driving a 0-10 V signal.

The existing building exhaust fans were retrofitted with Magnatek VFDs to balance the aggregate total of outside-air intake. The Magnatek VFDs were specified with factory-installed Siemens S600 FLN (field level network) cards to facilitate the connection to the S600 BAS without having to 'hardwire' each I/O point into the S600 control cabinet; this arrangement saved labor and the expense of individual I/O modules while simultaneously providing much more motor performance data to the building owner.

Completing the BAS component changes were the addition of one Setra building static pressure sensor that was essential to ensure a positive pressure in the whole building relative to the outside.

No other major control components were required for the case study building; however, the application of a new and fairly complex control strategy was essential to execute the DCV application. The DCV control algorithm is the most critical aspect of the project, as failure to implement an effective control sequence will yield lower energy savings performance.

Building Upgrade Assessment

Building owners must be able to evaluate the energy-saving potential and cost of specific initiatives to weigh the value of various building upgrade options. The methodology used to assess the potential of CO_2-based ventilation control involved five basic steps.

1. Spot measurement of CO_2 levels
2. Trend logging of CO_2 and other environmental factors
3. Estimation of the savings potential
4. Implementation assessment
5. Payback analysis

1. Spot measurement of CO_2

As indicated previously, CO_2 concentrations can be correlated to cfm/person ventilation rates inside a space. For a preliminary assessment of ventilation rates for this building, a number of spot measurements of CO_2 concentrations were made on each floor. A hand-held CO_2 monitor was used that is capable of calculating the cfm/person ventilation rate based on inside/outside differential CO_2 concentrations. The monitor assumes outside concentrations are 400 ppm, but it will also allow the baseline concentration to be set based on an actual outside measurement.

Spot measurements for CO_2 were made in the mid-morning to late morning and late afternoon hours on weekdays, after occupancy had stabilized in the building. They were taken while the building was not operating in economizer mode.

The results of the spot measurements showed that most areas of the building under study had CO_2 concentrations below 700-800 ppm, corresponding to ventilation rates in the range of 28 to 35 cfm/person. These rates were well over the original design target of 20 cfm/person. The chart shows the correlation between peak CO_2 levels

Figure 5. Handheld CO_2 sensor with cfm/person calculation and data logging.

and cfm/person ventilation rates, assuming office-type activity and an outside level of 400 ppm. Based on the spot measurements, it appeared that this building could be a good candidate for energy savings through better control of ventilation. These results warranted further investigation.

2. Trend logging of environmental factors

Trend logging was conducted over 7 typical days in the building to ensure that representative conditions were being measured. Ideally, measurements should be made in the major occupancy zones on each floor. If many locations are involved and monitoring devices are limited, multiple measurement sessions may be necessary. Devices used for measurement should measure CO_2 and should be able to log concentrations to a database every 15 minutes for a period of a week (at least 672 data points per parameter measured). Typically, data-logging sensors come with software to adjust, download and graph the results.

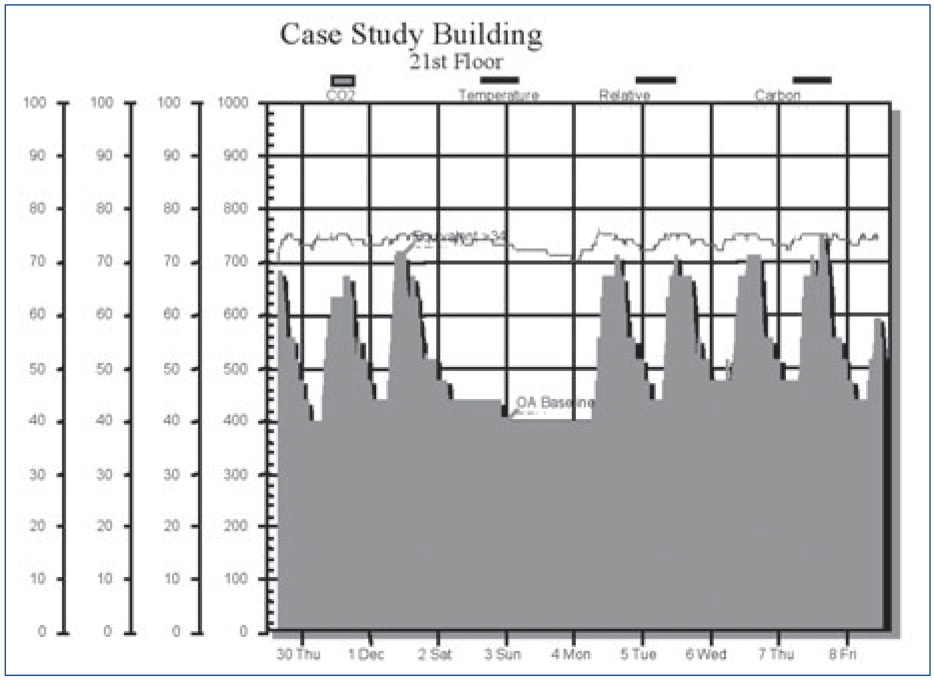


Figure 7. CO_2 trend-logged results from 7 days of monitoring of one location in the building.

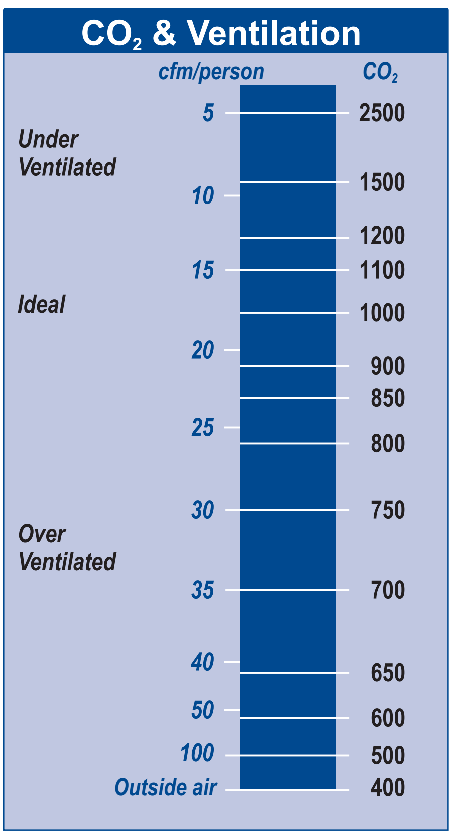


Figure 6. CO_2 to ventilation rate conversion, assuming 400 ppm outside and office-type activity (1.2 MET).

Several locations in the building were monitored over 7 days. Results of trend logging verified that the building was over-ventilated compared with the original design. The ventilation rate can be determined by looking at portions of the graph that show extended periods of operation where the CO_2 levels have stabilized; these indicate that the amount of CO_2 produced by people has reached equilibrium with the ventilation rate of the space. These periods are represented by the flat areas at the peak of each of the daily trend logs. In almost all locations, CO_2 levels and calculated ventilation rates were similar to those recorded during spot measurements. In general, peak levels around 930 ppm indicate a ventilation rate of 20 cfm/person; peak levels near 1100 ppm would indicate ventilation rates of 15 cfm/person. At the peak values recorded in the chart (674 ppm on average), the effective delivered amount of fresh air per person was more than 34 cfm/person, or 170% of the design need of 20 cfm/person. During periods of lower occupancy throughout the day and during Saturday morning operation, the effective delivered cfm/person considerably exceeded design needs and resulted in the use of excess energy to condition the surplus outside air.

Over-ventilation in the space may be due to either space densities being below original design conditions or the upward adjustment of outside air delivery to the building over design conditions. The building operator indicated that during summer months, occupants in the building often complained of uncomfortable humidity levels, indicating that perhaps the existing system was introducing more outside air than the system was originally designed for. This often happens when building operators “tweak” the building control system or air intakes to respond to complaints or to better tune the “feel” of the building. Based on hundreds of measurements in buildings throughout the country, over-ventilation appears to be a common problem in office buildings.

3. Savings potential/pre-project energy analysis

A number of CO_2 sensor manufacturers offer software to analyze the cost savings that will result from applying a CO_2 ventilation control based on occupancy versus a strategy of fixed ventilation during all occupied hours. These programs typically use local hourly weather data and energy cost data. They focus on the energy required to heat and cool various quantities of outside air delivered to the building without undertaking a full-blown energy performance analysis of the building. A similar analysis can be performed using more elaborate building analysis programs such as DOE2.

Using one manufacturer's CO_2 software, the case study building was modeled floor-by-floor to assess the potential annual energy savings. Ventilation rates determined from the trend logging were used to calculate the current fixed ventilation rate by multiplying the cfm/person of ventilation air by the typical peak occupancy on the floor observed during the trend-logged period. For CO_2 control, the modeling program assumed a control algorithm that would proportionately modulate air delivery based on the CO_2 concentration, a typical ventilation control strategy used with CO_2 sensing. It also allowed for simulated occupancy patterns to be varied every 30 minutes to reflect typical occupancy variations through the day. The program correlates the hourly ventilation load with hourly normalized outdoor temperature and dewpoint climactic data to provide an accurate assessment of the HVAC load during all hours while accounting for days when economizer operation results in zero savings as a result of the '"free cooling" effect.

For the case study building, the CO_2 modeling program projected that annual savings of excess of \$81,293 would be achievable based on normalized climatic data. Based on energy costs in 2000, these savings are equivalent to a 10% reduction in total energy costs, an average of \$3000 in savings per floor annually, and \$0.22 per square foot of gross area per year.

4. Implementation assessment

Most floors in the building had open floor plans, with perimeter offices in some cases. In most cases, office doors remained open during occupied hours, allowing free flow of ventilation air between the open central area and the offices. For these floors, it was decided to place one CO_2 sensor on the wall in each quadrant of the building. The rationale for such spacing was that each sensor would cover an area of no greater than 3600 ft^2 of open floor, and two sensors would provide input to each AHU. To ensure that all spaces were adequately ventilated, the ventilation is controlled based on the highest (or worst-case) level of the paired CO_2 sensors. It is important to note that duct sensors were not used because they tend to reflect an average ventilation rate rather than what is actually occurring in the space.

One of the floors had a large number of enclosed meeting/training/video-conferencing rooms that were not often all occupied at the same time. One CO_2 sensor was installed in each of those rooms. In many instances, inter-zonal transfer of air from spaces with lower CO_2 levels will moderate the amount of outside air that must be delivered to the floor, particularly if all rooms are not occupied.

The AHU on each floor required that the relay-operated outside air damper actuator be replaced with a fully modulating electrical motorized actuator to allow modulation of air delivery to each floor. To alleviate the constant negative pressure relationship in the building, the original building static pressure sensor located at the highest point within the building (in the elevator shaft, for unknown reasons) was disconnected. A new building static pressure sensor was located off the lobby level, on the lee side of the building and of the prevailing winds to minimize false positive or negative readings. For the twin exhaust fans, VFDs were added to balance the outside air intake with the required exhaust while maintaining a positive-pressure relationship with the outside. The new outside air CO_2 sensor was installed on the roof, away from any building exhaust and the effects of street-level fluctuations in CO_2.

Critical tasks a building control system or a supporting control and logic system must be able to perform for CO_2 control include these:

- Take input from a number of CO_2 sensors on a floor and determine the highest level.
- Modulate a signal to an actuator or variable-speed fan serving each floor to proportionally modulate the delivery of air based on the CO_2 concentration measured on the floor.
- Control the central building air intake so demand to the entire building can be modulated based on the demand of each floor. (Often a pressure sensor in the main supply air trunk can ensure adequate air delivery.)

Summary of projected energy savings from CO_2 control

Energy	Electricity		Steam		Total
	kWh	Cost[a] (\$)	Therms	Cost[b]	
Base	13,966,500	670,800	147,756	122,591	793,391
With CO_2	12,513,896	601,075	134,758	111,023	712,098
Savings	1,452,604	69,725	12,998	11,568	81,293
Savings (%)	10.4		8.8		10.2

[a] Electricity cost = \$0.48 per kWh.
[b] Steam cost = \$0.89 per therm (natural gas source @81% efficiency).

In summary, the work required to upgrade the building included

- Installing a minimum of four CO_2 sensors and two VFD drives on each of the air intakes for each floor and interfacing these devices to the building control system.
- Programming the building control system to take the CO_2 transmitter signal and regulate air delivery on each floor based on in-space CO_2 levels.
- Moving and replacing the building static pressure sensor.
- Installing variable-speed drives on the building exhaust fans.

It is important to note that for CO_2 control to work in a building, all other HVAC-related systems must be in good operating order. CO_2-related investigations may identify problems not previously recognized and add cost to an upgrade project. In this building, the assessment identified problems with the location of the building pressurization sensor, which had to be relocated and replaced. Logging of CO_2 concentrations in the spaces also indicated that the time-of-day operating schedules on some floors did not match actual occupancy patterns, and a change was recommended. In some cases, a regular check of logged CO_2 data from permanently installed sensors can help keep time-of-day schedules relevant to current occupancy patterns. In some cases, CO_2 data have been used to detect end-of-day occupancy and initiate setback operation when inside levels approach outside concentrations.

5. Payback analysis

The total cost of the building upgrade, including equipment and labor, was estimated at $178,800, which also included $15,000 for the for the pre-project trend analysis. Based on the projected cost savings of $81,293 the CO_2 upgrade project was projected to yield a 2.2-year payback. Based on this methodology and analysis, the project was initiated by the building owner in the late spring of 2001 and completed in July of that year.

Summary of BLCC 5.1-03 life-cycle cost analysis

Study Period 15 years Discount Rate 3%	Base: Current Operational/No CO_2 Control	Retrofit of Self Calibrating CO_2 Control	Saving from CO_2
Initial Investment: Cash Requirements	$	$178,800.00	$ (178,800.00)
Future Cost			
Annual & non-annual recurring cost	$	$	$
Energy related cost	$9,414,476	$8,460,875	$953,602
Total	$9,414,476	$8,460,875	$953,602
Net Savings			
PV of non-investment savings			$953,602
Increased total investment			$178,800
Savings-To-Investment Ratio			5.33
Adjusted Internal Rate of Return			15.66%
Simple Payback			3 years
Discounted Payback			3 years

Life-Cycle Cost Analysis

A life-cycle cost analysis of this project using BLCC 5.1-03 was performed using energy and cost data for the building collected for the year 2000 but based on an April 2003 start date, as required by the BLCC program. This procedure probably results in an analysis based on slightly lower costs in the analysis than prevail currently. The study period of 15 years was selected because this is the typical life of most electronic control devices. If a longer period is desired, the user should account for replacement of the sensors at the end of year 15 (approximate cost is $250 to $350 per replacement sensor, including labor). In performing the CO_2 portion of the study, no annual or periodic costs were assumed. In this case, we assumed use of self-calibrating sensor that require no maintenance or calibration over their operating life. Some sensors do require periodic calibration at 3 to 5 years, and users are urged to consider this fact in the selection and cost analysis of their particular installation. The cost of calibration will vary depending on the manufacturer and procedures required. About a third of the sensors sold today have a self-calibrating feature that eliminates maintenance requirements.

The total cost of the building upgrade, including equipment and labor, was estimated at $178,800 (including $15,000 for pre-project trend analysis). The projected annual cost savings was $81,293. The upgrade project was projected to yield a 2.2-year payback.

Post-Implementation Experience

After 6 months of operation, energy data from the building were collected to determine how the CO_2 retrofit and other improvements to the building were performing. Unfortunately, because of changes resulting from a company reorganization, a full 12 months of performance data was not available for analysis. Figure 6 provides a summary of the energy usage for each half-year period during 2000 and 2001. The CO_2 ventilation control system was operated from July to December of 2001. As can be seen from the data, the reductions in energy consumption were in excess of the savings predicted. The difference is probably due to a number of factors, including these:

- Replacement and relocation of the building pressurization sensor probably impacted energy savings, but savings were not predicted for this improvement.
- Time-of-day schedules were reprogrammed based on actual occupancy, and building exhaust fans were adjusted to minimum levels during unoccupied hours. The change that probably contributed additional energy savings to savings predicted.
- The year 2001 was milder than 2000 and had 20% fewer cooling degree days and 4% fewer heating degree days.

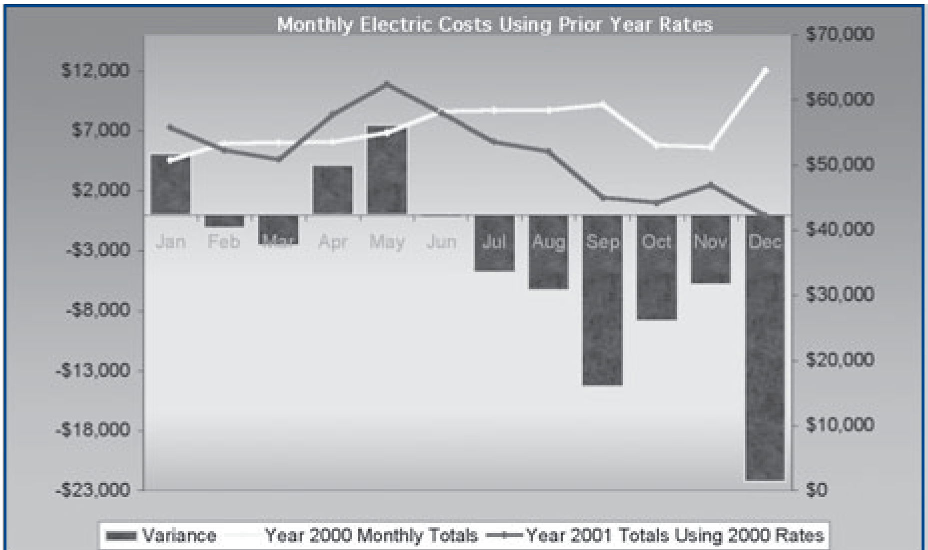
According to the facility manager, the tenants were satisfied with the comfort levels in the space following the retrofit and no longer complained of high humidity levels in the building during summer months. Because the logged CO_2 data showed the space to be significantly over-ventilated, reducing ventilation with CO_2 control reduced the amount of humid outside air drawn into the building and allowed the cooling system to maintain better control of humidity.

The following charts show energy performance, electricity costs, and steam costs before and after the CO_2-based DCV retrofit.

Before-and-after energy performance

Energy Cost	2000		2001	
	Jan–June	July–Dec	Jan–June	July–Dec*
Electricity kwh	6,357,000	7,609,500	6,606,000	6,219,000
Electricity ($)	$305,136	$365,256	$317,088	$298,512
Steam (therm)	71,918	75,838	84,523	22,960
Steam ($)	$64,007	$67,496	$75,225	$20,434
Total ($)	$369,143	$432,752	$392,313	$318,946
Annual ($)		$801,895		$711,260
6 month savings comparing July–Dec 2000 vs 2001				
Electric ($)				$66,744
Steam ($)				$47,061
Total ($)				$113,805

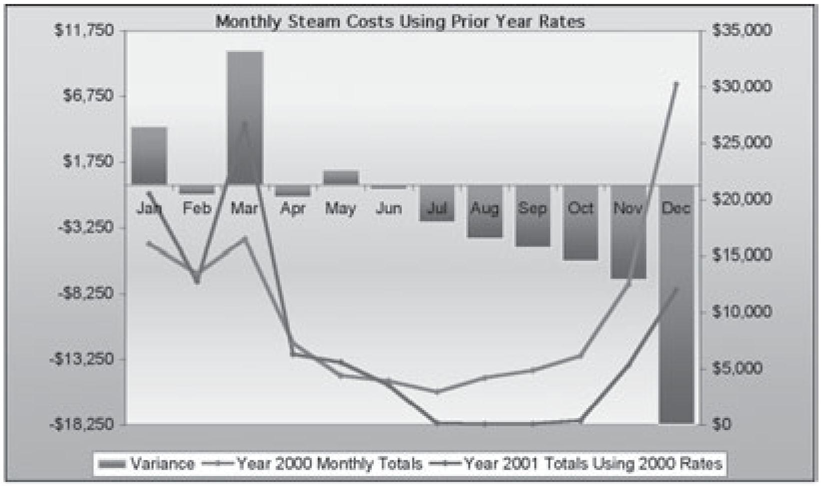
*CO_2 Control in Operation



	Monthly Kwh Usage 2000	Year 2000 Cost Per Kwh	Year 2000 Monthly	Monthly Kwh Usage 2001	Year 2001 Totals Using 2000 Rates	Variance
Jan	931,500	$0.0545	$50,751	1,024,500	$55,817.49	$5,067
Feb	1,032,000	$0.0517	$53,344	1,011,000	$52,258.07	-$1,085
Mar	1,035,000	$0.0516	$53,421	985,500	$50,866.04	-$2,555
Apr	1,042,500	$0.0514	$53,607	1,123,500	$57,772.45	$4,165
May	1,095,000	$0.0502	$54,962	1,245,000	$62,490.63	$7,529
Jun	1,221,000	$0.0477	$58,212	1,216,500	$57,997.49	-$215
Jul	1,227,000	$0.0476	$58,382	1,126,500	$53,599.93	-$4,782
Aug	1,297,500	$0.0450	$58,381	1,156,500	$52,036.64	-$6,344
Sep	1,317,000	$0.0450	$59,319	999,000	$44,995.94	-$14,323
Oct	1,123,500	$0.0472	$53,042	936,000	$44,189.89	-$8,852
Nov	1,153,500	$0.0458	$52,777	1,024,500	$46,874.76	-$5,902
Dec	1,491,000	$0.0433	$64,545	976,500	$42,272.43	-$22,273

Figure 8. Shown are the monthly costs (right scale) for the ‘baseline’ months 2000 (light line) and for the months of 2001 (dark line) calculated using 2000 rates. The variance (left scale) is shown by the columns. A major vector change occurred beginning in July (as the first phases of DCV were coming on-line) that is known not to be weather related (the minor variance in Feb/Mar is known to reflect a shift in the weather load).

Before and After Steam Usage for Case Study Building



	Monthly Steam Usage 2000	Year 2000 Cost Per M^3 Lbs	Year 2000 Monthly	Monthly Steam Usage 2001	Year 2001 Totals Using 2000 Rates	Variance
Jan	1,647	$9.7365	$16,036	2,103	$20,475.88	$4,440
Feb	1,259	$10.7220	$13,499	1,189	$12,748.43	-$751
Mar	860	$19.1683	$16,485	1,395	$26,739.80	$10,255
Apr	672	$10.8123	$7,266	585	$6,325.20	-$941
May	366	$12.0920	$4,426	462	$5,586.49	$1,161
Jun	333	$11.7691	$3,919	304	$3,577.80	-$341
Jul	270	$10.9787	$2,964	11	$120.77	-$2,843
Aug	333	$12.6317	$4,206	6	$75.79	-$4,131
Sep	381	$12.7423	$4,855	5	$63.71	-$4,791
Oct	523	$11.7887	$6,166	33	$389.03	-$5,776
Nov	1,166	$10.7147	$12,493	495	$5,303.78	-$7,190
Dec	2,744	$11.0335	$30,276	1,090	$12,026.47	-$18,249

Figure 9. Shown are the monthly costs (right scale) for the 'baseline' months in 2000 (lighter line) and the cost for the months of 2001 (darker line) calculated using 2000 rates. The variance (left scale) is shown by the columns. Since July, savings have occurred each month as a direct result of the CO_2 retrofit project, whereas the variance in March 2001 is known to be due to a shift in weather load.

The Technology in Perspective

The Technology's Development

CO_2-based DCV is an emerging technology with currently limited but increasing market penetration. The literature on CO_2-based DCV consistently predicts that the technology will become a common ventilation strategy.

CO_2 sensors for DCV regulation are a relatively mature product, having been on the market since about 1990. The first CO_2 sensors were expensive, unreliable, and difficult to keep calibrated. However, manufacturers claim to have resolved those problems—units currently available generally are self-calibrating and similar to thermostats in price and reliability. Although manufacturers say most sensors are designed to operate for 5 years without maintenance, regular inspection to verify calibration and proper operation is still recommended.

Interest in DCV was spurred by ASHRAE 62, which increased the requirement for ventilation air in buildings to safeguard IAQ. Building managers became concerned that the increased ventilation level was driving up energy costs by introducing unnecessarily large amounts of fresh air that had to be cooled, heated, dehumidified. CO_2-controlled DCV offers a method of regulating ventilation levels so as to satisfy the requirements of ASHRAE 62 without over-ventilating.

DCV based on CO_2 sensing is recognized as a viable strategy by the HVAC and building industries:

- CO_2 sensors are sold by all major HVAC equipment and controls companies.
- More than a dozen manufacturers produce CO_2 sensors for DCV.
- Most manufacturers of thermostats and economizers now integrate CO_2 sensors into their products, and major manufacturers of packaged rooftop HVAC systems offer factory-installed CO_2 sensors as an option.
- ASHRAE 90 requires CO_2 sensors for DCV in high-density applications.
- In the next revision of its building code, California will begin requiring CO_2-based DCV in all buildings housing 25 people or more per 1000 ft^2.
- A proposed change in the Oregon building code would require DCV for HVAC systems with ventilation air requirements of at least 1500 cfm, serving areas with an occupant factor of 20 or less.
- ASHRAE Standard 62, the IMC (which establishes minimum regulations for mechanical systems), and some state and local building codes recognize CO_2-based DCV.
- The U.S. Green Building Code gives points in its LEED rating system for use of CO_2-based DCV.

Technology Outlook

CO_2-based DCV appears likely to become a commonplace ventilation strategy for large commercial and institutional buildings as building operators seek ways to balance building code ventilation requirements and IAQ concerns with the need to control energy demand and operating costs. Equipment development is encouraging the adoption of the technology. Prices of CO_2 sensors for DCV prices have dropped by about 50% since 1990, and as market penetration increases, are expected to fall further. Most HVAC equipment makers are including factory installation of CO_2 sensors for DCV as an option in their large packaged systems. At least one major manufacturer has adapted its equipment line to accommodate CO_2-based DCV in every piece of ventilation equipment it makes. This implicit endorsement of the technology by equipment makers makes its adoption simpler and less expensive, at least in new installations, and will almost certainly contribute to developing a broader market for CO_2-based DCV.

The emergence of wireless, self-powered multi-parameter (CO_2/temperature/humidity) sensors designed for permanent installation is expected to further increase the speed of adoption of DCV. They have the potential to lower the total cost of deployment, making installation simpler and faster and improving paybacks.

As installers, HVAC engineers, and maintenance personnel accumulate more hands-on experience with the controls and operational issues CO_2-based DCV presents, and gain more expertise in troubleshooting and resolving problems, the comfort level with the technology should increase. The increased familiarity is likely to increase its acceptance.

Manufacturers

The following list includes companies identified as manufacturers of CO_2 sensors for demand-controlled ventilation at the time of this report's publication. The list does not include manufacturers of CO_2 sensors designed for use in safety equipment or for control of conditions in laboratories or industrial processes that are not appropriate for demand-controlled ventilation. We made every effort to identify all manufacturers of the equipment, including an extensive search of the *Thomas Register*; however, this listing is not purported to be complete or to reflect future market conditions.

AirTest Technologies
1520 Cliveden Avenue
Delta, BC V3M 6J8
Tel: 888-855-8880, 604-517-3888
Fax: 604-517-3900
www.airtesttechnologies.com
mike.schell@airtesttechnologies.com

Carrier Corporation
6304-T Thompson Rd., P.O. Box 4808
Syracuse, NY 13221 4808
Tel: 315-432-6000
www.carrier.com/

DetectAire, Inc.
5973 Encina Road, Suite 109
Goleta, California 93107
Tel: 805-683 1117
www.detectaire.com
(DetectAire markets wireless sensors)

Digital Control Systems, Inc.
7401-T S.W. Capitol Hwy.
Portland, OR 97219 2431
Tel: 503-246-8110 Fax: 503-246-6747
http://www.dcs-inc.net

Honeywell Control Products
11 W. Spring St.
Freeport, IL 61032
Tel: 815-235-6847 Fax: 815-235-6545
Cable: Honeywell-Freeport
http://www.honeywell.com/sensing

Johnson Controls, Inc.
Controls Group
507 E. Michigan St., P.O. Box 423
Milwaukee, WI 53201 0423
Tel: 800-972-8040 Fax: 414-347-0221

Kele
3300 Brother Blvd.
Memphis, TN 38133
Tel: 888-397-5353 Fax: 901-382-2531
Email: info@kele.com
www.kele.com

MSA
MSA Bldg., P.O. Box 426
Pittsburgh, PA 15230 0426
Tel: 412-967-3000
Fax: 412-967-3450 or 800-967-0398
Cable: MINSAF
http://www.msanet.com

Telaire Systems, Inc.
6489 Calle Real, Dept. TR
Goleta, CA 93117
Tel: 805-964-1699 Fax: 805-964-2129

Texas Instruments, Inc.
Commercial Sensors & Controls Div.
34 Forest St., MS 20-22, P.O. Box 2964
Attleboro, MA 02703-0964
Tel: 800-788-8661, Ext. 400
http://www.tisensors.com

Thermo Gas Tech
8407 Central Ave.
Newark, CA 94560
Tel: 888-243-6167 Fax: 510-794-6201
Or call: 510-745-8700
http://www.thermogastech.com

Vaisala, Inc.
100 Commerce Way
Woburn, MA 01801 1008
Tel: 800-408-5266 Fax: 781-933-8029
http://www.vaisala.com

Veris Industries, Inc.
16640 SW 72nd Ave.
Portland, OR 97224
Tel: 503-598-4564 Fax: 503-598-4664
http://www.veris.com

Who is Using the Technology

Federal Sites

The Pentagon
Robert Billak
Department of Defense
Pentagon Heating and Refrigeration Plant
300 Boundary Channel Dr.
Arlington, VA 22020

Navy Annex
Robert Billak
Department of Defense
Pentagon Heating and Refrigeration Plant
300 Boundary Channel Dr.
Arlington, VA 22020

Beaufort Marine Corps Air Station
Neil Tisdale, Utilities Director
Beaufort, South Carolina

Non-Federal Sites

Purdue University
Luci Keazer, P.E.
Facilities Service Department
1670 PFSB Ahlers Drive
West Lafayette, IN 47907
Lkeazer@purdue.edu

Oberlin University
Adam Joseph Lewis Center
for Environmental Studies
Leo Evans
122 Elm Street
Oberlin, Ohio 44074

Reedy Creek Energy Services (The Walt Disney Company)
Paul Allen
407-824-7577
paul.allen@disney.com

Shorenstein Realty Services
Bob Landram
816-421-4997
blandram@shorenstein.com

For Further Information

Associations

American Society of Heating, Refrigerating and Air-Conditioning Engineers
American Society for Testing and Materials
U.S. Green Building Council
American Indoor Air Quality Council

Design and Installation Guides

Demand Controlled Ventilation System Design, Carrier Corporation, Syracuse, NY, 2001
Application Guide for Carbon Dioxide Measurement and Control, Telaire Corporation, Goleta, California, 1994.

Manufacturer's Application Notes

"Reference Guide for Integration CO_2 DCV with VAV Systems," Telaire Corporation, October 2000. www.telaire.com/telaire.htm.

"Common CO_2 Wiring Issues," Telaire Corporation, October 2000, www.telaire.com/telaire.htm.

Publications

A.T. DeAlmeida and W.J. Fisk, Sensor-Based Demand Controlled Ventilation, LBNL-40599, UC-1600, Lawrence Berkeley National Laboratory, July 1997.*

M.J. Brandemuehl and J.E. Braun, "The Impact of Demand-Controlled and Economiser Ventilation Strategies on Energy Use in Buildings," ASHRAE Transactions, vol. 105, pt. 2, pp. 39–50, American Society of Heating, Refrigerating and Air-Conditioning Engineers, Atlanta, 1999.*

M.J. Brandemuehl and J.E. Braun, "The Impact of Demand-Controlled Ventilation on Energy Use in Buildings," p. 15, paper RAES99.7679 in Renewable and Advanced Energy Systems for the 21st Century, RAES 1999 Proceedings, R. Hogan, Y. Kim, S. Kleis, D. O'Neal, and T. Tanaka, eds., American Society of Mechanical Engineers, New York, 1999.**

S.C. Carpenter, "Energy and IAQ impacts of CO_2-Based Demand-Controlled Ventilation, ASHRAE Transactions, vol. 102, pt 2., pp. 80–88, American Society of Heating, Refrigerating and Air-Conditioning Engineers, Atlanta, 1996.**

S.J. Emmerich and A.K. Persily, "Literature Review on CO_2-Based Demand-Controlled Ventilation," ASHRAE Transactions, vol. 103, pt. 2, pp. 229–243, American Society of Heating, Refrigerating and Air-Conditioning Engineers, Atlanta, 1997.*

Electric Power Research Institute, Office Complexes Guidebook, Innovative Electric Solutions, TR-109450, October 31, 1997.

W.J. Fisk and A.T. DeAlmeida, "Sensor-Based Demand Controlled Ventilation: A Review," Energy and Buildings, 29(1) (March 1), 1998.**

S. Gabel and B. Krafthefer, Automated CO_2 and VOC-Based Control of Ventilation Systems Under Real-Time Pricing, EPRI-TR-109117, Electric Power Research Institute, Palo Alto, California, and Honeywell Technology Center, Minneapolis, Minnesota, October 1998.**

D. Houghton, "Demand-Controlled Ventilation: Teaching Buildings to Breathe," E Source Tech Update TU-95-10, E Source, Boulder, Colorado, 1995.*

D.B. Meyers, H. Jones, H. Singh, P. Rojeski, "An In situ Performance Comparison of Commercially Available CO2 Sensors, pp. 45–53 in Competitive Energy Management and Environmental Technologies: Proceedings, Association of Energy Engineers, Atlanta, 1995. **

B.A. Rock and C.T. Wu, "Performance of Fixed, Air-side Economizer, and Neural Network Demand-Controlled Ventilation in CAV Systems, ASHRAE transactions, vol. 104, pt 2., pp. 234–245, American Society of Heating, Refrigerating and Air-Conditioning Engineers, Atlanta, 1998.

* Publication that provided information for this document.
** Publication retrieved from NISC/BiobliLine.

K.W. Roth, D. Westpalen, J. Dieckmann, S.D. Hamilton, and W. Goetzler, Energy Consumption Characteristics of Commercial Building HVAC Systems Volume III: Energy Savings Potential, TIAX 68370-00, TIAX, LLC, Cambridge, MA, July 2002.*

M.B. Schell and D. Inthout, "Demand Control Ventilation," ASHRAE Journal, American Society of Heating, Refrigerating and Air-Conditioning Engineers, Atlanta, February 2001.*

M.B. Schell, S.C. Turner, and R.O. Shim, "Application Of CO2 Demand-Controlled Ventilation Using ASHRAE 62: Optimizing Energy Use And Ventilation," ASHRAE Transactions, vol. 104, pt. 2, pp. 1213-1225, American Society of Heating, Refrigerating and Air-Conditioning Engineers, Atlanta, 1998.*

M. Schell, "Real-Time Ventilation Control," Heating, Piping, Air-Conditioning Engineering, Interactive Feature, April 2002.* www.hpac.com/member/feature/2002/0204/0204schell.htm

Case Studies

Adam Joseph Lewis Center for Environmental Studies, www.oberlin.edu/envs/ajlc/ (Building Systems, Heating and Air Quality, Indoor Air Quality)

Codes and Standards

Ventilation for Acceptable Indoor Air Quality, ASHRAE Standard 62-2001, American Society of Heating, Refrigerating and Air-Conditioning Engineers, Atlanta. www.ashrae.org.

Energy Standards for Buildings Except Low-Rise Residential Buildings, ASHRAE Standard 90.1-2001, American Society of Heating, Refrigerating and Air-Conditioning Engineers, Atlanta. www.ashrae.org.

American Society of Testing and Materials Standard D6245-98, *Standard Guide for Using Indoor Carbon Dioxide Concentrations to Evaluate Indoor Air Quality and Ventilation*

2000 International Mechanical Code, International Code Council, Falls Church, Virginia.

2001 California Building Standards Code, Title 24, *California Code of Regulations*, Part 4: California Mechanical Code, California Building Standards Commission, Sacramento, California.

Appendix A

Federal Life-Cycle Costing Procedures and the BLCC Software

Federal agencies are required to evaluate energy-related investments on the basis of minimum life-cycle costs (10 CFR Part 436). A life-cycle cost evaluation computes the total long-run costs of a number of potential actions, and selects the action that minimizes the long-run costs. When considering retrofits, sticking with the existing equipment is one potential action, often called the *baseline* condition. The life-cycle cost (LCC) of a potential investment is the present value of all of the costs associated with the investment over time.

The first step in calculating the LCC is the identification of the costs. *Installed Cost* includes cost of materials purchased and the labor required to install them (for example, the price of an energy-efficient lighting fixture, plus cost of labor to install it). *Energy Cost* includes annual expenditures on energy to operate equipment. (For example, a lighting fixture that draws 100 watts and operates 2,000 hours annually requires 200,000 watt-hours (200 kWh) annually. At an electricity price of $0.10 per kWh, this fixture has an annual energy cost of $20.) *Nonfuel Operations and Maintenance* includes annual expenditures on parts and activities required to operate equipment (for example, replacing burned out light bulbs). *Replacement Costs* include expenditures to replace equipment upon failure (for example, replacing an oil furnace when it is no longer usable).

Because LCC includes the cost of money, periodic and aperiodic maintenance (O&M) and equipment replacement costs, energy escalation rates, and salvage value, it is usually expressed as a present value, which is evaluated by

$$LCC = PV(IC) + PV(EC) + PV(OM) + PV(REP)$$

where PV(x) denotes “present value of cost stream x,”
IC is the installed cost,
EC is the annual energy cost,
OM is the annual nonenergy O&M cost, and
REP is the future replacement cost.

Net present value (NPV) is the difference between the LCCs of two investment alternatives, e.g., the LCC of an energy-saving or energy-cost-reducing alternative and the LCC of the existing, or baseline, equipment. If the alternative’s LCC is less than the baseline’s LCC, the alternative is said to have a positive NPV, i.e., it is cost-effective. NPV is thus given by

$$NPV = PV(EC_0) - PV(EC_1)) + PV(OM_0) - PV(OM_1)) + PV(REP_0) - PV(REP_1)) - PV(IC)$$

or

$$NPV = PV(ECS) + PV(OMS) + PV(REPS) - PV(IC)$$

where subscript 0 denotes the existing or baseline condition,
subscript 1 denotes the energy cost saving measure,
IC is the installation cost of the alternative (note that the IC of the baseline is assumed zero),
ECS is the annual energy cost savings,
OMS is the annual nonenergy O&M savings, and
REPS is the future replacement savings.

Levelized energy cost (LEC) is the break-even energy price (blended) at which a conservation, efficiency, renewable, or fuel-switching measure becomes cost-effective (NPV >= 0). Thus, a project’s LEC is given by

$$PV(LEC*EUS) = PV(OMS) + PV(REPS) - PV(IC)$$

where EUS is the annual energy use savings (energy units/yr). Savings-to-investment ratio (SIR) is the total (PV) savings of a measure divided by its installation cost:

$$SIR = (PV(ECS) + PV(OMS) + PV(REPS))/PV(IC).$$

Some of the tedious effort of life-cycle cost calculations can be avoided by using the Building Life-Cycle Cost software, BLCC, developed by NIST. For copies of BLCC, call the EERE Information Center (877) 337-3463.

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About FEMP's New Technology Demonstrations

The Energy Policy Act of 1992 and subsequent Executive Orders mandate that energy consumption in federal buildings be reduced by 35% from 1985 levels by the year 2010. To achieve this goal, the U.S. Department of Energy's Federal Energy Management Program (FEMP) sponsors a series of activities to reduce energy consumption at federal installations nationwide. FEMP uses new technology demonstrations to accelerate the introduction of energy-efficient and renewable technologies into the federal sector and to improve the rate of technology transfer.

As part of this effort, FEMP sponsors the following series of publications that are designed to disseminate information on new and emerging technologies:

Technology Focuses—brief information on new, energy-efficient, environmentally friendly technologies of potential interest to the federal sector.

Federal Technology Alerts—longer summary reports that provide details on energy-efficient, water-conserving, and renewable-energy technologies that have been selected for further study for possible implementation in the federal sector.

Technology Installation Reviews—concise reports describing a new technology and providing case study results, typically from another demonstration program or pilot project.

Other Publications—we also issue other publications on energy-saving technologies with potential use in the federal sector.

More on Federal Technology Alerts

Federal Technology Alerts, our signature reports, provide summary information on candidate energy-saving technologies developed and manufactured in the United States. The technologies featured in the FTAs have already entered the market and have some experience but are not in general use in the federal sector.

The goal of the FTAs is to improve the rate of technology transfer of new energy-saving technologies within the federal sector and to provide the right people in the field with accurate, up-todate information on the new technologies so that they can make educated judgments on whether the technologies are suitable for their federal sites.

The information in the FTAs typically includes a description of the candidate technology; the results of its screening tests; a description of its performance, applications, and field experience to date; a list of manufacturers; and important contact information. Attached appendixes provide supplemental information and example worksheets on the technology.

FEMP sponsors publication of the FTAs to facilitate information-sharing between manufacturers and government staff. While the technology featured promises significant federal-sector savings, the FTAs do not constitute FEMP's endorsement of a particular product, as FEMP has not independently verified performance data provided by manufacturers. Nor do the FTAs attempt to chart market activity vis-a-vis the technology featured. Readers should note the publication date on the back cover, and consider the FTAs as an accurate picture of the technology and its performance at the time of publication. Product innovations and the entrance of new manufacturers or suppliers should be anticipated since the date of publication. FEMP encourages interested federal energy and facility managers to contact the manufacturers and other federal sites directly, and to use the worksheets in the FTAs to aid in their purchasing decisions.

Federal Energy Management Program

The federal government is the largest energy consumer in the nation. Annually, the total primary energy consumed by the federal government is 1.4 quadrillion British thermal units (quads), costing $9.6 billion. This represents 1.4% of the primary energy consumption in the United States. The Federal Energy Management Program was established in 1974 to provide direction, guidance, and assistance to federal agencies in planning and implementing energy management programs that will improve the energy efficiency and fuel flexibility of the federal infrastructure.

Over the years, several federal laws and Executive Orders have shaped FEMP's mission. These include the Energy Policy and Conservation Act of 1975; the National Energy Conservation and Policy Act of 1978; the Federal Energy Management Improvement Act of 1988; the National Energy Policy Act of 1992; Executive Order 13123, signed in 1999; and most recently, Executive Order 13221, signed in 2001, and the Presidential Directive of May 3, 2001.

FEMP is currently involved in a wide range of energy-assessment activities, including conducting new technology demonstrations, to hasten the penetration of energy-efficient technologies into the federal marketplace.

A Strong Energy Portfolio for a Strong America

Energy efficiency and clean, renewable energy will mean a stronger economy, a cleaner environment, and greater energy independence for America. Working with a wide array of state, community, industry, and university partners, the U.S. Department of Energy's Office of Energy Efficiency and Renewable Energy invests in a diverse portfolio of energy technologies.

Log on to FEMP's Web site for information about New Technology Demonstrations

www.eere.energy.gov/femp/

You will find links to

- A New Technology Demonstration Overview
- Information on technology demonstrations
- Downloadable versions of publications in Adobe Portable Document Format (pdf)
- A list of new technology projects under way
- Electronic access to a regular mailing list for new products when they become available
- How Federal agencies may submit requests to us to assess new and emerging technologies

For More Information

EERE Information Center
1-877-EERE-INF or
1-877-337-3463
www.eere.energy.gov/femp

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Energy Efficiency and Renewable Energy
Bringing you a prosperous future where energy is clean, abundant, reliable, and affordable