energydesignresources

design brief

DEMAND-CONTROLLED VENTILATION

How to improve building performance by varying the amount of outside air delivered to a space based on carbon dioxide concentration.

Summary

Demand-controlled ventilation (DCV) is a control strategy that varies the amount of ventilation outside air delivered to a space based on input from a single carbon dioxide (CO_2) sensor or group of sensors, which is representative of the quantity of occupants within the space. This strategy provides an accurate and appropriate amount of outside air to the space based on actual occupant density, as opposed to a constant outside air amount based on the design occupancy of the space.

Concerns about rising energy costs and a growing interest in Leadership in Energy and Environmental Design (LEED®) Green Building Rating Systems™ are making DCV an increasingly popular control strategy in new building construction and existing building retrofits. When properly applied, DCV lowers utility bills by reducing the amount of outside air that must be heated, cooled or dehumidified. When applied incorrectly, it can create negative building pressures, undesirable infiltration, and poor indoor air quality.

This design brief provides an overview of ventilation requirements for various codes and standards, an introduction into the design and application of DCV, a discussion on commissioning, energy modeling issues, and estimated energy savings from implementing DCV strategies. Additionally, this brief also provides information on various CO_2 sensor types.

CONTENTS

Introduction

DCV is a control strategy that varies the minimum ventilation outdoor air based on occupancy. Currently, the most economical way to measure occupancy in a building is through the use of CO_2 sensors. If it were economically feasible to count each person as they entered and exited from a space, then such a system could provide a more accurate method to meet the ventilation needs of the space. Realistically, occupancy in buildings is not tracked in real-time. Therefore, building engineers have sought other indicators of the quantity of persons within a space. Currently, tracking CO_2 is known to be an accurate and economically feasible indicator.

Up until the early 1990s, the engineering community has been required to design HVAC (heating, ventilation, and air-conditioning) systems that always provide enough ventilation air to satisfy maximum occupancy in a space (with some component of diversity allowed in the calculations). However, the HVAC design industry realized that because there is a high percentage of time when buildings are not fully occupied, it would be acceptable to reduce the amount of ventilation air by implementing a control strategy such as DCV.

The primary benefit of implementing a DCV strategy is a reduction in energy consumption, because the building's HVAC system must condition ventilated outside air to match indoor temperatures and humidity set points. Decreasing the intake of outside air below the design minimum when occupancy levels are low reduces the amount of energy required to heat, cool and dehumidify the air. For constant volume air-handling units, the savings occur at the primary systems (boilers, chillers, air-conditioners, etc.), and for variable-air-volume (VAV) air-handling units, the savings occur at the primary systems and at the terminal boxes that include reheat.

Other benefits can include improved indoor air quality and humidity control. With DCV, if a building automation system is monitoring CO_2 sensors, an air-handling system also has the capability to sense poor indoor air quality and increase the ventilation for the space to acceptable levels. This would occur if the number of occupants in the space is greater than what the engineer intended. The engineer can choose to use feedback from the sensors to increase the outdoor air intake past the design airflow, if necessary. For humid climates, DCV reduces the amount of moist

CO_2 Basics

- Measured in parts per million (ppm).
- Outdoor air CO_2 concentrations range between 300 and 500 ppm, and indoor CO_2 levels are rarely lower than the outdoor levels.
- Indoor CO_2 levels in a typical office building range between 400 and 900 ppm, and generally only rise above 1,000 ppm during a high occupancy event, or when the ventilation system is not performing properly.
- Adjacent spaces are only affected by this through re-circulated air that occurs at an air handler.
- CO_2 does not travel through walls, floors or ceilings in noticeable concentrations.

outside air that is brought into the space, which helps to mitigate comfort and mold issues.

Studies of indoor environmental quality in the built environment show a strong relationship between ventilation and occupant health and well-being. An assessment of indoor environmental quality studies from the 1990s shows that 70 percent of 22 studies illustrate a statistically significant correlation between increased indoor CO_2 concentration levels and Sick Building Syndrome (SBS) – unpleasant health effects that people can experience when spending time in buildings but decrease in severity when away from buildings.[1] An elevated CO_2 concentration has been shown to be an indicator of human-generated bioeffluents that cause SBS, including acetone, ammonia, methane, and volatile organic compounds. Ventilation standards are designed to ensure building occupants are provided with enough outdoor air to minimize adverse health effects such as SBS.

Codes and Standards

The application of DCV, as it relates to specific codes and standards, is important in understanding where and how a designer can implement the strategy. ASHRAE 62.1-2004, Ventilation for Acceptable Indoor Air Quality, the latest standard providing recommended ventilation rates, does not specifically require DCV, but does say it is an acceptable way to reset outdoor air intake flow as a result of variations in occupancy. Title 24, California's Energy Efficiency Standards for Residential and Non-Residential Buildings, requires DCV for certain non-residential space types. ASHRAE 90.1-2004, Energy Standard for Buildings Except Low-Rise Residential Buildings, requires DCV in spaces that receive at least 3,000 cfm of outdoor air and have an occupant density greater than 100 people per 1,000 square feet. The United States Green Building Council's (USGBC) Leadership in Energy and Environmental Design (LEED) rating system, adopted by many organizations and jurisdictions throughout the US, includes CO_2 monitoring as a method of compliance for certain credits.

ASHRAE 62.1-2004

ASHRAE 62.1- 2004[2] is a ventilation standard that explains how to design and construct a space that has an acceptable quantity of ventilation air. This document is a standard, and is only used as a code when a local governing body adopts this standard as part of the local mechanical code.

The 2004 version of the standard explains how to calculate the minimum amount of fresh air that is needed to maintain a space at acceptable air quality conditions. Two parameters are required to calculate the outside air requirement for a specific space: the area of the space in question and the occupant density of the space in question. The per person portion of the total accounts for the amount of outside air necessary to remove any effluents such as human-induced odors, and the per floor area portion is the amount necessary to remove any non-biological odors and contaminants, such as gases produced by interior objects like office chairs, carpeting or merchandise, and building objects such as paint. **Equation 1** shows these variables and an example calculation.

Equation 1: Minimum Outside Air

The following equation provides an estimate of the minimum amount of outside air necessary for proper indoor environmental quality, according to ASHRAE 62.1-2004. Tables referenced in this equation can be found in the standard.

Total Min OA = Air_p *P + Air_a *A

Where:

- Total Min OA = The total outside air requirement (cfm)
- Air_p = Outdoor air flow rate required per person (cfm; see Table 6-1)
- P = Zone population. Typically the largest quantity of people expected to occupy the space, or an average based on section 6.2.6.2.
- Air_a = Outdoor air flow rate required per ft^2 (cfm; see Table 6-1)
- A = Zone floor area (ft^2)

As an example, a typical office space has the following numbers (the unit cfm indicates cubic feet per minute and ft^2 is square feet.)

Air_p = 5 cfm/person

Air_a = 0.06 cfm/ft^2

Based on a typical occupant density of five people per 1,000 ft^2, this results in a minimum outside airflow of 17 cfm per person.

Source: Architectural Energy Corporation

Additional Factors

Additional factors can increase or decrease the amount of minimum outside air. One of these factors involves the zone air distribution effectiveness. The air distribution configuration will affect this distribution effectiveness, and the designer must account for this in the minimum outside airflow calculation. Table 6-2 in the ASHRAE 62.1 standard lists the zone air distribution effectiveness values that must be applied based on configuration type, and can increase the minimum outside air amount by up to 50 percent or decrease it by as much as 20 percent.

For multizone systems, the mechanical designer must also account for the system ventilation efficiency in the minimum outdoor airflow calculation. Depending on the ratio of minimum outside air to the total airflow, the engineer may need to increase the amount of outside air if the ratio is greater than 15 percent. Table 6-3 in the standard lists the fractions used to calculate this increase in the minimum outdoor air amount, which can be as great as 40 percent or more.

VAV systems also warrant special consideration according to this standard. For a VAV system, the design must be capable of delivering the required ventilation rate under all part-load conditions. If the system is not capable of modulating the minimum outdoor air fraction as the total airflow amount changes, the minimum outdoor air fraction must be calculated to still provide the minimum outdoor air amount during the period of lowest airflow.

For example, a VAV system with a static minimum outdoor air fraction provides 10,000 cfm total, and is required to provide 1,000 cfm of outside air. This would suggest that the minimum outdoor air fraction should be 10 percent. However, since this fraction is not being adjusted based on total airflow, the minimum outdoor air fraction needs to be adjusted, so the minimum outdoor air amount is maintained at any supply airflow. Given this example, if the system is expected to modulate the airflow as low as 40 percent, or 4,000 cfm, the actual minimum outdoor air fraction that needs to be used is 1,000 cfm/4,000 cfm, or 25 percent outside air.

DCV is acceptable to meet the requirements in ASHRAE 62.1. The standard describes the idea that because occupancy can vary within a space, the minimum outside air amount can be adjusted lower than the calculated minimum based on input from an occupant counter, schedule or CO_2 sensor. Further, in Appendix C of the standard, it is explained that if the indoor space is maintained at a CO_2 level no greater than 700 ppm above outdoor ambient, then “a substantial majority of visitors entering a space will be satisfied with respect to human bioeffluents.”

In this brief, the adjusted amount of outside air is referred to as the “lower limit.” It is the smallest amount of outside air the space can intake to remain code compliant when nobody is in the space. The non-adjusted amount, the amount of outside air designers must calculate to determine cooling/heating coil sizes, is the minimum outside air quantity, but is also reffered to as the "upper limit" when discussing DCV. Together, the two limits form the range of outside air the space requires to satisfy code. Any amount of outside air less than the upper limit will produce energy savings.

Therefore, when both concepts presented are applied, deductive reasoning implies that it will be acceptable to vary the outdoor air quantity between the amount calculated based on zero occupants and the amount required with full occupancy. In the typical office building, this results in a range of 60 cfm of outside air per 1,000 ft^2 when minimally occupied, and 85 cfm of outside air per 1,000 ft^2 when fully occupied. In a system that has an average airflow of 1 cfm/ft^2 and serves 100,000 ft^2, the range of required outside air is between 6,000 cfm and 8,500 cfm, depending on occupancy. When applied to other occupancy categories, this approach results in a reduction of 20 to 30 percent of the ventilation air during low occupancy conditions.

Title 24-2005

Title 24-2005 has many similarities to ASHRAE Standard 62.1-2004 with respect to the application of DCV strategies.[3] Section 121 in this energy efficiency standard explains the requirements of minimum ventilation air and the application of DCV. Some important differences are:

- DCV is required in single-zone HVAC spaces that have an economizer and serve a space with a design occupant density, or a maximum occupant load factor for egress purposes in the California Building Code, of 25 people per 1,000 ft^2 or greater (with a few exceptions).
- The indoor CO_2 set point is 600 ppm above outdoor ambient.
- If outdoor CO_2 is not measured, then the outdoor CO_2 level is assumed to be equal to 400 ppm.

For Title 24, one important requirement states that when the HVAC system is operating during normal occupied hours, the ventilation rate while DCV is active is not allowed to drop below the values listed in Title 24 Table 121-A, multiplied by the floor area of the conditioned space. The ventilation rate found in this table for a typical office building is 0.15 cfm/ft^2, which results in 15,000 cfm of minimum outside air for the typical 100,000 ft^2 office building, as compared to 0.06 cfm/ft^2 in ASHRAE 62.1, which results in 6,000 to 8,500 cfm of outside air for the same sized building.

Therefore, as a side by side comparison of different energy standards, the following ventilation rates apply.

Table 1: Comparison of Ventilation Requirements

With an applicable area of 100,000 ft^2, the outside air requirement for a K-12 school can decrease by as much as 78 percent of the design minimum.

Code/Standard	Building Type	Lower Min OA Airflow (cfm)	Upper Min OA Airflow (cfm)	Percent OA Reduction
ASHRAE 62.1-2004	Office	6,000	8,500	29%
Title 24-2005	Office	15,000[a]	15,000	0%
ASHRAE 62.1-2004	K-12 School	12,000	47,000	74%
Title 24-2005	K-12 School	15,000	67,500	78%

[a] In an office environment with low occupant density, the area based minimum outdoor airflow is often equal to the maximum required ventilation rate. Therefore, Title 24 only shows energy savings due to DCV in spaces that have considerably higher occupancy densities than office buildings.

An important concept to note from **Table 1** is that DCV does not offer a large reduction in outside air during times of low occupancy when applied to a typical office building. However, DCV can offer a large reduction in minimum ventilation air to spaces that are designed to be more densely populated such as schools, auditoriums, and other spaces that have large variations in occupant population.

ASHRAE 90.1-2004

ASHRAE Standard 90.1-2004[4] mandates that all air-handling systems with an outdoor air capacity greater than 3,000 cfm serving areas having an occupant density greater than 100 people per 1,000 ft^2 include DCV as a control strategy, or any other strategy with the ability to reduce the outdoor air intake automatically. The one exception to this rule is if the system incorporates a method of energy recovery, such as an enthalpy wheel. According to the standard, spaces with occupant densities greater than 100 people per 1,000 square feet include:

- lecture halls with fixed seats
- multi-purpose assembly rooms such as hotel conference rooms and convention centers

- public assembly auditoriums, lobbies and places of worship
- spectator areas in sport facilities
- gambling casinos

Other space types that are suitable for DCV, but are not required to include DCV as a control strategy include museums, theaters, gymnasiums, cafeterias, bars, transportation waiting areas, and dance clubs, per the ASHRAE standard.

LEED® NC 2.2

The USGBC created the LEED® rating system[5] to create a consistent method for owners and designers to design and build an environmentally responsive buildings. Within this program are credits that directly discuss CO_2 sensor use as it pertains to indoor air quality, not energy savings.

LEED® for New Construction v2.2 Indoor Environmental Air Quality (IEQ) credit 1 states that when the indoor CO_2 levels vary by more than 10 percent above or below ASHRAE 62.1-2004 requirements, then the mechanical control system shall be able to send an alarm informing the occupants to take corrective action. Designers can take this a step further by creating a control sequence that allows the outside air damper to open past its minimum position, as set by the Test, Adjust, and Balance contractor. This will provide more fresh air to the space, however, the mechanical system might be pressed to do more work than it can handle if the outdoor conditions are close to design conditions.

How to Implement DCV

Design Considerations

A common misconception among HVAC designers is that CO_2-based DCV is a method to guarantee fresh air to a space, even during high-occupancy events when CO_2 concentrations exceed the space CO_2 set point. Systems with this style of DCV strategy could lead to uncomfortable conditions. Designers should note that when DCV is being actively used during a high CO_2 event, the outdoor air damper must not be opened beyond the minimum fresh air setting because the coils are not sized to handle more outdoor air than originally calculated, unless the unit is in economizer mode. Heating, cooling, and dehumidification coils are typically sized to meet their heat transfer load during design conditions (winter, summer, wet-bulb, etc) assuming the maximum amount of outdoor air that is entering the air handler is the required minimum ventilation based on full occupancy (potentially with some diversity component). Consequently, in some cases, the coils that HVAC designers specify for air handlers are not capable of meeting the temperature or humidity load when the quantity of outdoor air entering an air handler is greater than the quantity that was incorporated into the coil sizing load calculations.

To control the quantity of outside air correctly using DCV, the design engineer should carefully evaluate the space and HVAC system in order to select an appropriate strategy. The most common DCV strategy requires two outside air volume set points, a lower and an upper outside airflow set point, when the building is occupied. The upper set point is the maximum amount of fresh air that a DCV system will allow when the indoor CO_2 concentration surpasses its set point (typically 700 ppm greater than the outside air CO_2 concentration). It also is the maximum amount of outside air that the coils are capable of handling, as previously mentioned. The minimum set point is the lower limit of the outside air amount that the system will intake, occurring when indoor CO_2 concentrations are equal to outdoor concentrations. For proper implementation, this lower limit set point must take into account general exhaust requirements and indoor pollutant sources, such as carpet and paint off-gassing—otherwise, the strategy will potentially cause a negative building static pressure and harmful indoor environmental quality for occupants.

An alternate strategy, called Supply Air CO_2 Control (SACO_2), controls the outside air ventilation rate based on the CO_2 concentration of the supply air (see "Supply Air CO_2 Control").

Supply Air CO_2 Control

Several engineers from Canada have developed an alternative strategy for multi-zone air handling systems based on the supply air CO_2 concentration. Unlike other strategies, it does not require varying occupancy patterns. Supply air CO_2 ($SACO_2$) control is a technique for measuring the outdoor air fraction in the supply air to control the outdoor air intake. This technique ensures that the supply air always contains a high enough fraction of outdoor air to ventilate any space served by the system. It is applicable to recirculating systems serving multiple spaces where ventilation targets are based on outdoor airflow rate per person. The use of $SACO_2$ control reduces reheat and fan energy, ensures good ventilation, minimizes installation and maintenance costs, allows for the ability to measure and record performance, and is easily applied to new or existing buildings.

As the total number of building occupants varies, the unused outdoor air content and the CO_2 concentration in the recirculated air varies. The CO_2 sensor detects the effect this has on the supply air and, unless more outdoor air is needed for makeup or free cooling, the $SACO_2$ system adjusts the outdoor air intake to maintain a CO_2 set point in the supply air; the set point is equivalent to the desired design minimum outdoor air fraction in the supply air. Outdoor air often enters through windows and doors, transfers from adjacent systems with a ventilation surplus, or leaks from supply ducts into the return system. When such air is recirculated, the $SACO_2$ system detects the drop in the supply air CO_2 concentration and reduces the minimum outdoor air intake accordingly. Similarly, if the relief air short circuits into the outdoor air intake, the $SACO_2$ system detects the rise in CO_2 concentration and increases outdoor air intake as needed.

A single CO_2 sensor detects CO_2 concentration in the supply duct and outdoors via a three-way valve. A valve switches between sources and fan suction draws air through the sensor. The outdoor air intake is controlled so the rise in CO_2 concentration between outdoors and the supply air does not exceed a value that corresponds to the required minimum outdoor air fraction in the supply air. Maintaining a minimum level of ventilation air even during unoccupied periods is recommended to reduce odor and contaminant buildup and maintain building pressure control.

Key points with $SACO_2$ control:

- The control system should periodically sample the outdoor air CO_2 (the readings should be averaged to improve accuracy and stability) and frequently read the supply air CO_2.
- The cost is likely to be $500 plus $1,000/sensor plus general contractor's overhead and profit. Engineering costs are likely to be $2,000 plus $600/sensor.
- CO_2 sensors need periodic checking and recalibration (new sensors should be checked three months after installation and annually thereafter). With the right sensor, this is simple and takes 5-15 minutes. A specialist charges around $100/sensor.

When is DCV appropriate?

Choosing whether DCV is appropriate for a particular space depends on the following factors.

- Design occupant density – Spaces with higher-than-average occupant densities reap better benefits with DCV than spaces with low occupant densities. Higher occupant densities require greater quantities of outdoor air, which can be drastically reduced during low occupancy periods.
- Variability of occupancy in the space – Variability is critical because a space with a constant occupancy pattern, such as a warehouse or round-the-clock manufacturing facility, will always require the same amount of outside air. Without a varying occupancy, no need exists to reduce outside air quantities.

- Generation of indoor pollutants – The generation of indoor pollutants can alter the way a designer implements a DCV strategy. Pollutants require specific amounts of outdoor make-up air for dilution and exhaust. If the pollutants are severe enough, the make-up air requirement for the space may be large enough to warrant changes to the outside air intake quantities.

- Space heating and cooling loads – Space heating and cooling loads are dependent on indoor set points and the climate in which the building is located. Buildings in mild climates require less energy to meet set points than buildings in harsher climates. Thus, adding DCV to a building in a harsh climate will show greater energy savings than implementing DCV in a building located in a mild climate.

- Space pressurization requirements – Designers must take into account space pressurization requirements, specifically if make-up air and exhaust requirements are significant enough to maintain proper positive and negative space pressures.

- The information in **Table 2** can aid designers in choosing whether a particular space is suitable for DCV.[6]

Carbon Dioxide Sensors

Designers choosing DCV should consider a variety of specifications when selecting sensors. For example, because the indoor CO_2 concentration should never be above 1,500 ppm, an upper limit range of 2,000 ppm is appropriate for HVAC industry applications. Below is a list of CO_2 sensor specifications that are appropriate for DCV:

- Range: 0-2,000 ppm

- Accuracy (which includes repeatability, non-linearity and calibration uncertainty): +/- 50 ppm

- Stability (allowed error due to aging): <5% Full Scale for 5 years

- Linearity (maximum deviation between a reading and the sensor's calibration curve): +/- 2% Full Scale

- Manufacturer recommended minimum calibration frequency: 5 years

Table 2: DCV Suitability by Space Type

Not all spaces are suitable for DCV. Spaces not suitable include those with constant occupancy patterns, low occupant densities, specific pressurization requirements and make-up air requirements for harmful toxic chemicals.

Rating: A = Recommended B = Possiblea C = Not recommended

Application	Rating
Correctional facilities	
Cells	A
Dining halls[b]	B
Guard stations	C
Dry cleaners and laundries	
Commercial laundry	B
Commercial dry cleaner	C
Storage and pickup	B
Coin-operated laundries	A
Coin-operated dry cleaners	C
Education and schools	
Classrooms	A
Laboratories[d]	B
Training shops	B
Music rooms	A
Libraries	A
Locker rooms	C
Auditoriums	A
Smoking lounges	B
Food and beverage service	
Dining rooms[b]	B
Cafeteriasb	B
Bars, cocktail lounges[c]	B
Kitchens	C
Garages, repair and service stations	C

Application	Rating
Specialty shops	
Barber and beauty	B
Reducing salons	B
Florists	B
Clothiers	B
Furniture	B
Hardware	B
Supermarkets	B
Pet shops	C
Sports and amusement	
Spectator areas	A
Industrial facilities	
Heavy manufacturing	C
Light manufacturing	B
Materials storage	C
Training facilities	C
Painting and finishing areas	C
Food and meat processing	C
Office buildings	A
Retail stores	
Sales Floors	A
Dressing rooms	A
Malls and arcades	A
Shipping and receiving	C
Warehouses	C

Application	Rating
Hospitals and medical facilities	
Patient rooms	B
Medical procedure	C
Operating rooms	C
Recovery and ICU	B
Autopsy rooms	C
Physical therapy	A
Lobbies and waiting areas	A
Hospitals, resorts and dormitories	
Bedrooms	B
Lobbies	A
Conference rooms	A
Meeting rooms	A
Ballrooms and assembly	A
Gambling casinos	B
Game rooms	A
Ice arenas	A
Swimming pools	C
Gymnasiums	A
Ballrooms and discos	A
Bowling alleys	A
Theaters	A
Transportation	
Waiting rooms	A
Platforms	A

[a] Applications listed as "possible" may be suitable for demand-controlled ventilation. The system designer must evaluate additional factors such as building size and arrangement, type of HVAC system and separate requirements for control of contaminants not related to human occupancy.
[b] DCV may be a suitable application, however, adequate ventilation and system balancing is necessary to maintain pressurization and odor control.
[c] Designer must consider ventilation for cigar and cigarette smoke control.
[d] Ventilation system design must consider requirements for odor and vapor control plus separate requirements for fume hoods.

Source: Carrier Corporation [6]

Other considerations when specifying a sensor include whether or not it should be duct-mounted or wall-mounted, if it needs to be outdoor rated, and if an alarm dry contact relay is needed. Additionally, the designer should take into consideration the sensor's ease of calibration and whether it has an LED display to provide real-time readings on the front of the sensor. **Figures 1** and **2** show wall- and duct-mounted sensors. **Figure 3** shows an example CO_2 sensor specification sheet.

Sensor Quantity and Placement

Single Zone

Sensor location and quantity is a challenging topic, and does not result in definitive answers that are easily applied to all projects. What can be said with clarity is that a space that is served by a single-zone air handler can have, most often, one sensor located within the space at six feet above the finished floor. Most favorable applications include auditoriums, gymnasiums, conference rooms, and other large single-zone, single air-handling unit spaces.

The argument also can be made that measuring CO_2 in the return air duct of these spaces is acceptable, and sometimes even more representative of the room conditions. If the space is large, using one room-mounted sensor may not properly detect the CO_2 produced by occupants, whereas return air duct measurements can provide more accurate results.

Multiple Spaces

California's Title 24 may be the best reference for the quantity and placement of sensors with air handlers serving more than one zone. According to Title 24, if in a given zone, the design occupancy density is greater than 25 people per 1,000 ft^2, then the space would be considered a likely candidate for DCV and should receive its own sensor.

If Title 24 is not applicable to a project, then a designer should consider using fewer sensors and lowering the threshold set point to account for fewer CO_2 samplings. The result will be an increase in dilution of air within the space. An example application of this concept would involve

Figure 1: Wall-mounted CO_2 Sensors

Wall-mounted sensors should be placed in an area where the CO_2 concentration best represents the entire controlled zone.

Source: Vaisala Inc. [7]

Figure 2: Duct-mounted CO_2 Sensors

Duct-mounted sensors are more applicable to single-zone systems, and can be positioned in the return air duct.

Source: Vaisala Inc. [7]

Figure 3: CO_2 Sensor Cutsheet

This portion of Vaisala's GMD20 duct-mounted sensor specification sheet shows the necessary information to make informed decisions.

Performance

Carbon dioxide measurement	
Measurement range	0...2000 ppm (nominal; can be calibrated for other ranges: 0...5000 ppm, 0...10,000 ppm, 0...20,000 ppm)
Accuracy (including repeatability, non-linearity and calibration uncertainty)	± (2 % of range + 2% of reading)
Long-term stability	<±5 % of range / 5 years
Response time (63%)	1 minute
Warm-up time	1 minute, 15 minutes full specifications
Temperature measurement (optional with GMW21)	
Output signal	0...10V
Corresponding measurement range	0...+50 °C (32...+122 °F)
Accuracy at +25 °C	±0.5 °C (±0.9 °F)
Warm up time	30 min
Temperature sensor	Semiconductor IC

Inputs and outputs

Outputs	0...20 or 4...20 mA and 0...10 V
Optional outputs	relay LonWorks® interface
Resolution of analog outputs	8 bits
Recommended external load:	
current output	max. 500 ohm
voltage output	min. 1 kohm
Operating voltage	nominal 24 VAC/DC (18...30 VDC)
Power consumption	<2.5 W

Operating environment

Temperature	-5...+45 °C (+23...+113 °F)
Humidity	0...85 %RH, non-condensing
Flow velocity (GMD20)	0...10 m/s
Electromagnetic compatibility	EN61326-1, Generic Environment

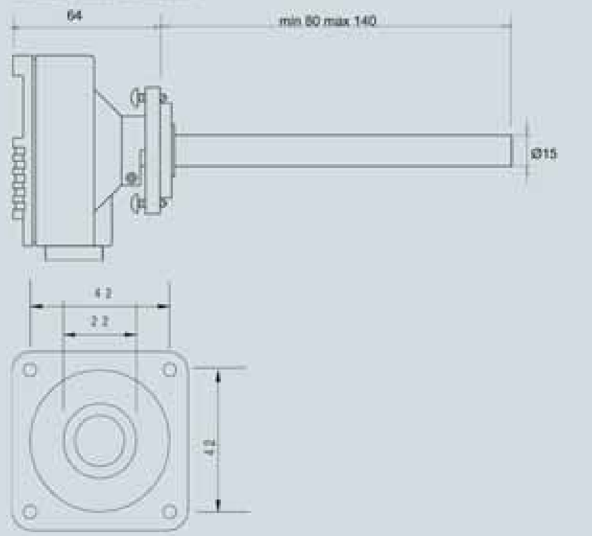
Mechanics

Housing material	ABS plastic
Housing classification (GMD20 electronics housing)	IP65
Weight:	
GMD20 (D)	140 g (170 g)
GMW21 (D)	100 g (130 g)
GMW22 (D)	90 g (120 g)

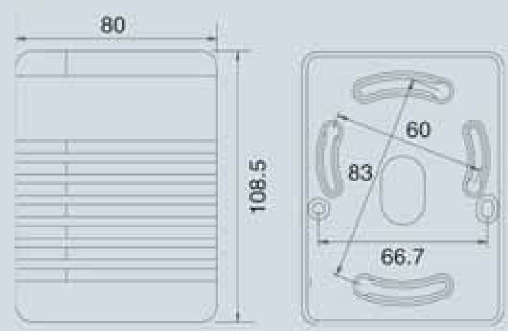
Dimensions

Dimensions in mm

GMD20 and GMD20D



GMW21 and GMW21D



Source: Vaisala Inc. [8]

placing a sensor in the return air duct of an air handler that serves multiple classrooms, and using an upper limit set point of 500 or 600 ppm above ambient (instead of 700 ppm). This approach creates a system that still reacts to an increase in occupancy, and accounts for the dilution that occurs in systems with larger supply airflow. The caveat to this approach is that the AHU system must be serving spaces that are occupied with very similar occupancy patterns and rates.

Multiple zones that are served by one air handler and are not loaded to the same level or frequency should have their own sensors, provided

DCV shows an opportunity to reduce outside air intake by a worthwhile amount. However, this can be an expensive alternative and may decrease system reliability, because adding multiple sensors to the system increases re-calibration requirements and the risk of faulty sensor readings.

Determining the Upper Limit

The upper limit for the most common DCV strategy is simply the minimum quantity of outside air, which design engineers must calculate for every air-handling system to size the heating and cooling systems. Though not requiring DCV for compliance, ASHRAE Standard 62.1-2004 shows (refer to Equation 1) how to calculate the minimum amount of fresh air that is needed to maintain a space at acceptable air quality conditions. In doing so, the outside air requirement calculations in this standard have become the standard practice for calculating the DCV upper limit for a particular air-handling system.

Determining the Lower Limit

The lower limit for controlling outdoor airflow using DCV is the amount of air necessary for proper air quality in a building with little or no occupancy. Without any people in the building, the air handling system must still provide the proper amount of outdoor air to relieve any buildup of indoor pollutants and keep moisture from entering through walls.

The lower minimum outdoor air flow rate specified also must account for building exhaust air flow rates, such that the minimum amount of fresh air that is required to maintain correct building pressure is always maintained. This means that the design engineer must specify in the mechanical schedule upper and lower minimum ventilation rate requirements, and the test, adjust, and balance contractor must coordinate with the controls contractor to program a sequence that properly modulates the damper between these values based on CO_2 readings. This approach will be valid for spaces that do not have stored chemicals or other items that would create poor indoor air quality undetectable by a CO_2 sensor.

Determining the lower limit involves the same process as determining the upper limit, but the calculation does not include the per person airflow requirement, but instead, includes the total exhaust airflow. **Equation 2** determines the minimum outdoor air flow rate.

Optinet: A New Approach to DCV

Aircuity, a manufacturer of sensing and controls solutions, has developed an air quality monitoring product that can sense CO_2 and other pollutants from one central monitoring station. Called Optinet, the system employs a backbone network of tubes “wired” to each space, similar to a main/branch plumbing system. Packets of air are sent via the tubes through a router to a central monitoring system, which then tests the air using a suite of sensors, including CO_2, relative humidity, volatile organic compounds, carbon monoxide and small particles (PM2.5), among others. The results are available on the internet and can be integrated with a building automation system for DCV and differential enthalpy economizer control.

For more information visit www.aircuity.com.

Equation 2: Minimum Outside Air

The equation calculates the lower limit minimum outdoor air flow rate for a space controlled with DCV.

Lower Limit = Air_a *A

Where:

- **Lower Limit = The total lower limit of outside air required (cfm)**
- **Air_a = Outdoor air flow rate required per unit area (cfm; see Table 6-1)**
- **A = Zone floor area (ft^2)**

Source: Architectural Energy Corporation

Table 3 shows several examples of the parameters necessary to calculate the upper and lower airflow limits, the results from the calculations, and how the results compare with each other.

Table 3: Outdoor Airflow for the Upper and Lower DCV Limits

Assuming the occupant density and outdoor airflow requirements outlined in ASHRAE 62.1-2004 Table 6-1, a DCV strategy will decrease the outdoor airflow for a 10,000 ft² auditorium with very few occupants to 93% of its design minimum.

Space Type	Floor Area	Occupancy Density (people/1000 ft²)	People Rate (CFM/person)	Area Rate (CFM/ft²)	Lower Min Outdoor Airflow (CFM)	Upper Min Outdoor Airflow (CFM)	% Difference
Retail	10,000	15	7.5	0.12	1200	2325	48%
Restaurant	10,000	70	7.5	0.18	1800	7050	74%
Auditorium	10,000	150	5	0.06	600	8100	93%
Health Club	20,000	40	20	0.06	1200	17200	93%
Elementary Classroom	20,000	15	10	0.12	2400	5400	56%
Office	50,000	5	5	0.06	3000	4250	29%
Museum	50,000	40	7.5	0.06	3000	18000	83%

Source: Architectural Energy Corporation

Control Sequences

The following are sample sequences of operation for a single-zone system that incorporates a DCV strategy.

Economizer Control

When the outdoor air conditions allow for economizer operation to occur, the mixed air damper shall modulate as needed to maintain the supply air temperature set point, and shall be subject to maintaining at least the minimum outside air setting. When the outdoor air conditions do not meet the economizer mode criteria, then the outside air damper shall be at its minimum setting (see below for a definition of "minimum setting").

- Minimum Outside Air Setting (Simplified): If the CO_2 sensor input is less than the set point, then the OA damper shall be at the lower minimum setting. Upon a rise in CO_2 sensor input greater than the set point, the OA damper shall modulate open, as needed, to increase the intake of OA. The maximum OA damper position during a high CO_2 event will not exceed the upper minimum ventilation rate as specified in the mechanical schedule.

- Minimum Outside Air Setting (with direct measurement of OA): The outside air damper shall modulate to maintain the minimum outdoor airflow set point, which is a value between the lower minimum and upper minimum quantities, based on the linear reset schedule shown in **Table 4**.

Table 4: Outside Air Ventilation Reset Schedule

Outdoor airflow can be proportionally controlled because the CO_2 concentration within a space is proportional to the number of occupants.

Space CO_2	Outdoor Airflow Set Point
100 ppm above ambient	Lower minimum OA set point
700 ppm above ambient	Upper minimum OA set point

Source: Architectural Energy Corporation

Both concepts presented above are acceptable, but the differences are worth understanding.

Concept #1 has an inherent time lag of response due to the fact that the outside air damper does not open more than its minimum setting until the space has crossed over its indoor CO_2 set point. The drawback to this approach is that the space will have brief times when the CO_2 in the space is above the set point until the newly introduced fresh air mixes in the space.

Concept #2 is preferred because it does not wait for the space to rise beyond set point before reacting. Instead, it tracks continuously to self-adjust and provide the minimum outdoor air that is needed at any given time to meet the ventilation demand. Additionally, direct measurement of the outdoor air is always preferred because it ensures that the correct amount of outdoor air is entering the air handling unit at all times. With multiple zone systems, the zone CO_2 controls should first increase the airflow rate at the space by increasing air terminal unit airflow (and subsequently reheat if applicable) and then increase the outdoor air rate at the air handler.

Cost Impacts and Maintenance Issues

The total cost of implementing DCV can be grouped into three main areas: hardware, engineering, and commissioning costs. Hardware costs include the price of the sensor(s) and the cost of installing the sensors.

The manufacturers' suggested retail prices for HVAC grade sensors in 2006 ranged between $200 and $630 (see **Table 5**)[9], with most in the $200-$350 range. Taking into account installation fees and contractor's markups, the installed cost ranges between $1,500 and $2,500 per sensor. The good news is sensor prices have declined in recent years, making DCV a more affordable energy-saving strategy.

Table 5: CO_2 Sensor Costs

Sensor costs have dropped dramatically since the mid 1990s, when prices were $500 and up.

Company	Recommended Frequency of Calibration	Cost Per Sensor
AirTest Technologies	Never needs calibration over its 145-year lifetime	$200
Digital Control Systems Inc.	5 years	$262
Honeywell Control Products	5 years or more	$350
Johnson Controls Inc.	5 years	$630
Telaire Systems Inc.	Guaranteed not to require calibration over the unit's expected 10-year lifetime	$150 to $200
Texas Instruments Inc.	3 years	$265 to $318
Vaisala Inc.	5 years	$335
Veris Industries Inc.	5 years	$378

Source: E Source [9]

The cost of engineering is minimal compared to the installed cost of the sensors. Engineering is comprised of the cost to calculate the upper and lower DCV limits, and write the sequence of operation, and the cost to have the controls engineer to program the BAS. Engineers knowledgeable with DCV strategies and implementation may only require an hour or two at their respective billing rates. If the engineers do not have experience designing DCV systems, or applies them incorrectly, additional time and expense may be required to properly implement DCV. The cost of commissioning a DCV system will be similar to the engineering cost. See the following section for information on the commissioning of DCV systems.

The only maintenance associated with DCV systems is ensuring the sensors are providing proper readings. Most sensors require calibration every three to five years to ensure proper readings throughout the life of the sensor. Additionally, it is important to review manufacturer maintenance and warranty information specific to each sensor. A building owner can purchase a CO_2 calibration kit for $200 to $300 and have in-house personnel perform the task, or they can hire professional services from a local company, which may cost approximately $100 per sensor.

Commissioning

Why is commissioning needed?

Building commissioning is a comprehensive and systematic process to verify that the systems within a building were designed, purchased, installed and controlled in accordance with the design intent, construction documents and specifications. Like any other building system component or energy-saving strategy, systems that incorporate DCV should be commissioned to ensure proper design, construction, and operation.

Recommendations

Commissioning DCV components and strategies is an ongoing process that includes activities throughout the project delivery process. California's Title 24 now has acceptance testing requirements for energy efficiency concepts, which include DCV. The Title 24 manual includes acceptance tests that the commissioning engineer can use to test DCV equipment and operation. The following is a list of activities that the commissioning authority should undertake on projects that incorporate DCV. Performing each task will ensure a functioning DCV strategy.

Design Phase Issues

- Verify that the commissioning specification is present and appropriate for the scope.
- Verify that the upper and lower minimum OA values are specified on the mechanical schedule (see **Figure 4**).[10]
- Verify that the sequences are properly written.

Figure 4: Mechanical Schedule Showing DCV

This portion of a rooftop unit schedule includes a minimum and a maximum outdoor airflow, indicating a DCV control strategy for RTU-2 and RTU-3.

DESIG.	AREA SERVED	MFR.	MODEL	NO. OF ZONES	CFM TOTAL @ 5300 FT	CFM O.A. @ 5300 FT	ESP IN. W.C. @ S.L.	TSP IN. W.C. @ S.L.	NO. FAN WHEELS
RTU-1	WEST CLASSROOMS	TRANE	T-SERIES SIZE 30	1	11,900	6,000	2.0	4.5	1
RTU-2	CAFETERIA/ FLEX ROOM	TRANE	T-SERIES SIZE 12	1	5,700	500 MIN/ 5,700 MAX	1.0	3.0	1
RTU-3	GYMNASIUM	TRANE	T-SERIES SIZE 12	1	6,000	500 MIN/ 6,000 MAX	1.0	3.0	1
RTU-4	CENTER CLASSROOMS/ MEDIA CENTER	TRANE	T-SERIES SIZE 30	1	10,000	4,500	2.0	4.5	1

Source: Schaffer □ Baucom Engineering & Consulting [10]

- Verify that the CO_2 sensor requirements are clearly and properly specified.
- Verify that the CO_2 sensors are located on plans, and the mounting height is clearly marked.

Submittal Phase Issues

- Verify that the submitted CO_2 sensor meets the specification requirements.
- Verify that the appropriate sensors have been selected for outdoor use, duct mount, or space mount.
- Verify that the control submittal reflects design requirements and all sensors have been incorporated into the engineered control submittal drawings.
- Verify that the "packaged" mechanical equipment factory wiring is compatible with submitted sensor.

Construction Phase

- Verify that the submitted (and approved) sensors have been installed in the correct locations, and have proper covers or guards as needed.

Acceptance Phase

- Perform a documented relative calibration check by recording the readings on all sensors early in the morning when there have been no occupants in the building for eight hours and the air handlers have been on for an hour or more. All sensors should read within 50-70 ppm. If not, they should be calibrated.
- Functionally test all DCV related sequences, including the worst case scenario of minimum flow, and then verify proper building pressurization is still maintained.
- Ensure that the owner's maintenance staff is aware of how to calibrate the sensors (calibration of new sensors is typically not necessary).

Seasonal Testing / Short-Term Monitoring

- Take trend data (1-2 weeks) on the CO_2 sensor signal, the damper operation of air handler and terminal units, exhaust fans status, and building pressure to validate proper operation under normal occupied operating conditions.
- Generate a report or memo with plots indicating proper operation of the DCV strategy.

Energy Modeling

Various modeling tools are available to help predict the energy impacts of controlling ventilation air with DCV. One cautionary note, as designers know, is energy modeling tools rely heavily on assumptions, and any variances between the assumptions and actual conditions will produce inconsistent results. Therefore, it is pertinent to use assumptions that are similar to the actual conditions as much as possible. When modeling DCV systems, the most important inputs are hourly occupancy patterns and occupant density.

Below is a brief discussion of the software tools that aid engineers in evaluating DCV.

DOE-2 Building Energy Analysis Program

DOE-2 is a building energy simulation tool, and one of the most widely-used simulation engines throughout the United States. Specific programming language has recently been added to version 2.2 that provides for simulation of different DCV strategies. By entering specific lines of code into the building description language (BDL), the input file for the DOE-2 software that describes every aspect of the building systems and how the BAS will control them, the user can simulate how several types of DCV strategies will function for single- and multiple-zone systems. The capability exists to simulate DCV by controlling the outside air volume with a sensor in the return air duct of a single-zone system, and with multiple sensors in spaces served with a multi-zone system. The user must indicate the chosen method at the SYSTEM level with the following code:

```
MIN-OA-METHOD    = DCV-RETURN-SENSOR    or
                 = DCV-ZONE-SENSORS
```

The user can also specify zone level control, to simulate VAV boxes that can have their minimum flow fraction reset upward (raised) or downward (lowered) due to DCV determined zone OA flow rate requirements. The following code is used at the zone level to establish this control:

```
MIN-FLOW-CTRL    = DCV-RESET-UP    or
                 = DCV-RESET-DOWN
```

eQUEST

eQUEST, short for the Quick Energy Simulation Tool, is a user-friendly graphical front-end, developed for Energy Design Resources that utilizes the DOE-2 simulation engine. It is currently popular with engineering consulting firms who provide energy modeling services. Although the DOE-2 program does have the capability to model DCV, at the time of publication, the eQUEST front-end did not yet have the capability to take advantage of these newer features. Thus, although eQUEST could aid in the general development of the model, the simulation of DCV would require the user to actually manipulate the DOE-2 programming. eQUEST is available for free at www.energydesignresources.com.

Virtual Environment

Virtual Environment (VE), a simulation tool developed by the United Kingdom firm Integrated Environmental Solutions Limited (IES), is similar to eQUEST in that it provides whole-building simulation analyses. However, it possesses some capabilities not available in eQUEST such as a module to support computational fluid dynamics analyses. VE can be purchased from the IES website, www.iesve.com.

Ventilation Strategy Assessment Tool

The Ventilation Strategy Assessment Tool (VSAT), developed by Jim Braun at Purdue University for the California Energy Commission's Public Interest Energy Research Program, is a tool that can simulate specific ventilation strategies for several common building types. The types include a small office building, a sit-down restaurant, a retail store, a school class wing, a school auditorium, a school gymnasium, and a school library. The tool's interface is easy and self-explanatory, and can calculate results with the input of several assumptions.

The tool was not created to be a design development tool but rather a parametric analysis tool, so it does have several limitations. For example, it can only simulate a building with either of two system types – a rooftop package unit with gas heat and a heat pump with electric backup heat. In addition, the user can only select weather files for the 16 California climate zones. The tool is available for download at www.energy.ca.gov/pier/final_project_reports/CEC-500-2005-011.html.

Energy Savings

The energy savings associated with DCV are the direct result of having less outside air to condition at the air handing unit, which reduces the energy required to cool, heat, and dehumidify the ventilation air. When the occupancy of the space served by the air handler is less than the maximum design occupancy, the application of DCV provides cost savings by reducing energy use.

Many factors can affect the energy savings associated with this control strategy. Some examples include:

- Occupancy schedule
- Space heating and cooling loads
- Ambient temperatures and humidity
- HVAC system type
- Amount of time the system is in economizer mode

Several studies have estimated energy and cost savings associated with the application of DCV control strategies on existing buildings. In a study by Jeannette et al,[11] the authors used DOE-2 to estimate energy savings and illustrate examples of the savings range that can be achieved. **Table 6** shows the results of this study.

The results shown in **Table 6** illustrate that energy savings can vary widely for the same building type in the same climate, from $0.04/ft^2 to as high as $0.34/ft^2, making it challenging to apply a "rule of thumb" for savings. Although no consistent rules apply, it is usually stated that DCV provides a cost-effective means for achieving considerable energy savings for larger spaces with significant variations in occupancy (such as cafeterias, gymnasiums, lecture halls, meeting rooms, etc.).

Table 6: Annual Energy Savings Estimates in Colorado

Implementing DCV on the same type of buildings in the same climate can result in a wide range of energy savings. A host of factors, including occupancy patterns and occupant density, greatly influence the strategy's ability to reduce energy consumption.

Building Type	Spaces DCV Applied	Location	Cost Savings ($/ft^2-y)
Elementary Schools (Range over 8 schools)	Gyms, large classrooms, media centers, auditoriums and cafeterias	Colorado Springs, CO	$0.09 - $0.33
Middle Schools (6 schools)	Gyms, large classrooms, media centers, auditoriums and cafeterias	Colorado Springs, CO	$0.05 - $0.20
High Schools (4 schools)	Gyms, large classrooms, media centers, auditoriums and cafeterias	Colorado Springs, CO	$0.05 - $0.14
University Building	Large classrooms and offices	Boulder, CO	$0.31
University Building	Large classrooms and offices	Boulder, CO	$0.34
University Building	Large classrooms, offices, lobby and conference room	Denver, CO	$0.23

Source: Architectural Energy Corporation

The results show that each potential application of DCV should be considered individually. Many variables affect energy savings in a specific application and should be appropriately weighed.

Conclusions

Sales of CO_2 sensors are on the rise, due to an increasing amount of building owners wanting to reduce energy costs and attempting LEED® certification.[12] CO_2 concentration is typically indicative of space occupancy, and can subsequently be used to determine the amount of ventilation air required for a given space at any given time. DCV controls vary the ventilation rate to limit CO_2 levels and subsequent levels of airborne contaminants. By reducing the ventilation rate during less occupied periods, energy is saved—in many cases significant amounts of energy—because the amount of outside air that must be heated, cooled, or dehumidified is reduced.

A building's potential for energy savings by implementing DCV is highly dependent on building occupant density, occupancy patterns, and heating and cooling load. If the building is ripe for DCV, it's up to the mechanical systems designer and commissioning team to make sure the system is designed, purchased, and functioning properly. If not, an inaccurate or vague design will lead to confusion and an underperforming system, and could end up costing the building owner more in energy than anticipated.

For More Information

CO_2 Sensor Manufacturers

Aircuity – www.aircuity.com

AirTest Technologies – www.airtesttechnologies.com

Carrier Corporation – www.carrier.com

Digital Control Systems, Inc. – www.dcs-inc.net

Honeywell Control Products – www.honeywell.com/sensing

Johnson Controls, Inc. – www.johnsoncontrols.com/cgsensors/CO2.htm

Telaire Systems, Inc. – www.gesensing.com/telaireproducts/

Texas Instruments, Inc. – www.tisensors.com

Vaisala, Inc. – www.vaisala.com

Veris Industries, Inc. – www.veris.com

Trade Associations

ASHRAE – www.ashrae.org

USGBC – www.usgbc.org

Publications

Warden, David. "Supply Air CO2 Control", *ASHRAE Journal*, October 2004.

Alpers, Robert, P.E., Jan Zaragoza. 1994. "Air Quality Sensors for Demand Controlled Ventilation", *Heating / Piping / Air Conditioning*, July: 89-91.

Emmerich, Steven J., Andrew K. Persily, PhD. 1997. Literature Review on CO2-Based Demand-Controlled Ventilation. *ASHRAE Transactions* 103 (2): 1-14.

Ke, Yu-Pei, Stanley A Mumma, Ph.D., P.E.. 1997. "Using Carbon Dioxide Measurements to Determine Occupancy Control for Ventilation Controls", *ASHRAE Transactions* 108 (2): 1-9.

Persily, Andrew K., PhD. 1997. "Evaluating IAQ and Ventilation with Indoor Carbon Dioxide", *ASHRAE Transactions* 108 (2): 1-12.

Schell, Mike, Dan Int-Hout. 2001. "Demand Control Ventilation Using CO_2", *ASHRAE Journal*, February: 18-29.

Sellers, Dave, Jerry Williams. "A Comparison of the Ventilation Rates Established by Three Common Building Codes in Relationship to Actual Occupancy Levels and the Impact of these Rates on Building Energy Consumption", *Commercial Buildings: Technologies, Design and Performance Analysis* (3): 299-314.

Notes

1 Seppanen, O.A., Fisk, W.J., and Mendell, M.J. (1999). Association of ventilation rates and CO_2 concentrations with health and other responses in commercial and institutional buildings. *Indoor Air*, vol. 9, pp. 226-252.

2 ASHRAE Standard62.1-2004, Ventilation for Acceptable Indoor Air Quality.

3 Title 24-2005 Building Energy Efficiency Standards. Subchapter 3: Nonresidential, High-Rise Residential, and Hotel/Motel Occupancies – Mandatory Requirements for Space-Conditioning and Service Water-Heating Systems and Equipment. 63-65.

4 ANSI/ASHRAE/IESNA Standard 90.1-2004, Energy Standard for Buildings Except Low-Rise Residential Buildings.

5 USGBC Leadership in Energy and Environmental Design (LEED®) Green Building Rating Systems™

6 Gia Oei (May 21, 2007), Director, Carrier Corporation, Farmington, CT, 860-674-3000.

7 Elizabeth Mann (April 18, 2007), Marketing Communications Manger, Vaisala Inc., Woburn, MA, 781-933-4500, Elizabeth.mann@vaisala.com.

8 Elizabeth Mann [7].

9 This information is copyrighted and was provided courtesy of E Source Companies, 1965 North 57th Court, Boulder, CO 80301, USA, 303-444-7788.

10 Barry Stamp (April 12, 2007), Principal, Schaffer Baucom Engineering and Consulting, Lakewood, CO, 303.986.8200, bstamp@sbengr.com

11 "Designing and Testing Demand Controlled Ventilation Strategies," *National Conference on Building Commissioning* (April 2006) from www.peci.org/ncbc/proceedings/2006/23_Jeannette_NCBC2006.pdf.

12 Criscione, P., Kamm, K., Greenberg, D. 2005. "Technological Advances Open Up New Opportunities for Demand-Controlled Ventilation", E Source, ER-05-2.

Energy Design Resources provides information and design tools to architects, engineers, lighting designers, and building owners and developers. Our goal is to make it easier for designers to create energy efficient new nonresidential buildings in California. Energy Design Resources is funded by California utility customers and administered by Pacific Gas and Electric Company, Sacramento Municipal Utility District, San Diego Gas and Electric, Southern California Edison, and Southern California Gas Company, under the auspices of the California Public Utilities Commission. To learn more about Energy Design Resources, please visit our Web site at www.energydesignresources.com.

This design brief was prepared for Energy Design Resources by Architectural Energy Corporation.

09/2007