NISTIR 7042

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ABSTRACT

Carbon-dioxide (CO_2) based demand controlled ventilation (DCV) offers the potential for more energy efficient building ventilation compared with constant ventilation rates based on design occupancy levels. A number of questions related to CO_2-based DCV have been raised concerning the indoor air quality impacts, primarily with respect to contaminants with source strengths that are not dependent on the number of occupants. In addition, questions exist regarding potential energy efficiency benefits, optimal control strategies for different building types, and sensor performance and deployment. In order to obtain some insight into the issue of IAQ impacts of CO_2-based DCV, a simulation study was performed in six commercial and institutional building spaces using the multizone airflow and IAQ model CONTAMW. These simulations compared seven different ventilation strategies, four of which used CO_2 DCV. The simulations, performed for six U.S. cities, were used to compare ventilation rates, indoor CO_2 levels, indoor concentrations of a generic volatile organic compound (VOC) as an indicator of non-occupant contaminant sources, and energy impacts. The results indicate that these impacts are dependent on the details of the spaces including occupancy patterns, design ventilation rate and ventilation system operating schedule, as well as the specific assumptions used in the analysis including contaminant source strengths and system-off infiltration rates. For the cases studied, the application of CO_2 DCV resulted in significant decreases in ventilation rates and energy loads accompanied by increased indoor CO_2 and VOC concentrations. The increases in CO_2 were not particularly large, in the range of 180 mg/m^3 (100 ppm(v)). The indoor VOC levels increased by a factor of two to three, but the absolute concentrations were still relatively low based on the assumed emission rates. The annual energy load reductions were significant in most of the cases, ranging from 10 % to 80 % depending on the space type, climate, occupancy schedule, and ventilation strategy.

Keywords: carbon dioxide, control, energy efficiency, indoor air quality, modeling, simulation, ventilation, volatile organic compounds

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TABLE OF CONTENTS

1. INTRODUCTION AND BACKGROUND

Commercial building ventilation systems are designed, installed and operated to heat and cool occupied spaces to achieve thermal comfort and to provide outdoor air to the occupants. Outdoor air ventilation is provided to buildings primarily to dilute contaminants that are generated by building occupants and their activities and by building materials and furnishings. The rate at which outdoor air is brought into a building by its ventilation system is determined during the building design based on requirements of applicable building codes and standards. For example, ASHRAE Standard 62-2001 (ASHRAE 2001a) and California Energy Efficiency Standards, so-called Title 24, (CEC 2001) contain minimum ventilation requirements for a number of different occupancy types in units of L/s (cfm) per person and in L/s per m^2 of floor area (cfm/ft^2).

Determining design outdoor air ventilation rates for commercial buildings using Standard 62-2001 or Title 24 is a relatively straightforward process. For each space served by a given ventilation system, one determines the expected or design number of occupants for space types with ventilation requirements in units of L/s (cfm) per person. In spaces with requirements in units of L/s-m^2 (cfm/ft^2), one determines the floor area. Based on the ventilation requirements contained in the standard, these values (number of people and floor area) are used to determine the L/s (cfm) of outdoor air required by that space under full occupancy. Standard 62-2001 also requires that these rates be adjusted to account for ventilation effectiveness (degree of ventilation air mixing in the space). Also, if the spaces are served by a system that recirculates air from multiple spaces and redistributes it along with “new” outdoor air, Standard 62-2001 requires the use of the so-called “multiple spaces” approach to determine the outdoor air intake rate. If no such recirculation occurs, then the outdoor air intake rate is equal to the sum of the outdoor air requirements for all the spaces served by the system, after adjusting for ventilation effectiveness.

ASHRAE Standard 62-2001 also allows for a reduction in the design occupancy under conditions of intermittent occupancy. Basically, the standard allows one to use the average occupancy instead of the design occupancy for spaces where the design occupancy is based on a peak lasting 3 h or less. However, one is not permitted to reduce the design occupancy by any more than 50 %. The average occupancy is then multiplied by the per person ventilation requirement for the space to determine the design outdoor air intake rate. Note that this reduction cannot also be employed when demand controlled ventilation is also used.

Demand controlled ventilation (DCV) is a ventilation rate control strategy to address the concern that when a space is occupied at less than its design occupancy, unnecessary energy consumption can result if the space is ventilated at the design minimum rate rather than the ventilation rate based on the actual occupancy. Furthermore, early during a given day of building occupancy, contaminants generated by people and their activities will not yet have reached their ultimate levels based on the transient nature of contaminant buildup. As a result, it is sometimes possible to delay or lag the onset of the design ventilation rate to take credit for this transient effect. A number of approaches have been proposed to account for actual occupancy levels and to provide the ventilation rate corresponding to actual rather than design occupancy. These include time-based scheduling when occupancy patterns are predictable, occupancy sensors to determine when people have entered a space (though not necessarily how many), and carbon dioxide (CO_2) sensing and control as a means of estimating the number of people in a space or the strength of occupant-related contaminant sources.

Controlling outdoor air intake rates using CO_2 DCV offers the possibility of reducing the energy penalty of over-ventilation during periods of low occupancy, while still ensuring adequate levels of outdoor air ventilation. As discussed later in this report, depending on climate and occupancy patterns, CO_2 DCV may provide significant energy savings in commercial and institutional buildings. While a number of studies have suggested the extent of such savings via field studies and computer simulations, additional work is needed to better define the magnitude of energy savings possible and the dependence of these savings on climate, building and system type, control approach, and occupancy patterns. In addition, important issues remain to be resolved in the application of CO_2 DCV including how best to apply the approach, which in turn includes issues such as which control algorithm to use in a given building, sensor location, sensor maintenance and calibration, and the amount of baseline ventilation required to control contaminant sources that don't depend on the number of occupants.

An earlier report presented a state-of-the-art review of CO_2 DCV technology and its application in commercial and institutional buildings (Emmerich and Persily 2001). That report presented discussions of CO_2 generation rates by people, the relationship of indoor CO_2 to building ventilation rates, and the basic concept of controlling ventilation based on indoor CO_2 levels. It also contained a literature review of previous research on CO_2 DCV, including field demonstration projects, computer simulation studies, studies of sensor performance and location, and discussions of the application of the approach. This earlier report and other discussions of CO_2 DCV identified indoor air quality impacts as an important issue in the application and performance of these systems. The key indoor air quality concern relates to contaminants that are generated in a building at a rate that does not depend on the number of occupants. For example, building materials and furnishings emit contaminants at an approximately constant rate independent of the occupancy level, including when the building is empty. Questions have been raised as to how well these contaminants will be controlled by a DCV system when the occupancy level is low. Some have proposed maintaining a minimum outdoor air ventilation rate at all times to control these contaminants, with the minimum based on a specific outdoor air intake rate per unit floor area expressed in L/s•m^2 (cfm/ft^2) (CEC 2001) or as a fraction of the design outdoor air intake rate, for example 25 % (Schell et al. 1998).

ASHRAE Standard 62-2001 allows for the outdoor air intake rate to be adjusted based on variations in occupancy (as noted earlier in the discussion of the intermittent occupancy approach), but regardless of the approach used to make these adjustments the system must still provide the required outdoor air ventilation rate per person. The standard does not explicitly discuss CO_2-based DCV in terms of sensor location, minimum outdoor airflow rates or other details. However, a number of official interpretations to the standard issued by ASHRAE make it clear that these approaches can comply with the standard if properly implemented. Title 24 also allows the use of demand controlled ventilation. If fact, it is required in spaces with high occupant densities as an energy efficiency measure.

As noted above, the outdoor air ventilation requirements in ASHRAE Standard 62-2001 are largely expressed as airflow rates per person in L/s•person (cfm/person). In some spaces, for example corridors and retail spaces, they are expressed in L/s•m^2 (cfm/ft^2) of floor area. The per person requirements are intended to address contaminants emitted by the occupants themselves as well as by the space they occupy, including building materials, furnishings and equipment. In developing the ventilation requirements per person, there is an implicit assumption as to the number of occupants per unit floor area in order to handle these non-occupant contaminants. If the space being designed has a different occupant density, it may receive more or less outdoor air than needed to handle the floor-area contaminants. In order to address that concern, a revision of the Ventilation Rate Procedure in ASHRAE Standard 62 has been developed that contains per person and per floor area outdoor air requirements for all spaces (Persily 2001). Under the revision, referred to as addendum 62n, one multiplies the number of people in a space by a per person ventilation requirement R_p and multiplies the floor area of the space by a per floor area requirement R_a. These two products are then added together to determine the outdoor air requirement in the occupied zone of the space. Further adjustments are required to account for mixing in the space and system effects in recirculating systems serving multiple spaces. This so-called additive approach has the advantage of addressing the concern about non-occupant contaminant sources and the provision of ventilation to handle these sources when occupancy is low or zero. It could also make the application of CO_2 DCV more challenging compared with ventilation requirements expressed solely in terms of per person rates, but control algorithms have been developed to implement CO_2 DCV for so-called “additive” ventilation requirements (Sowa 2002).

Resolving all the issues related to the application of CO_2 DCV in commercial buildings, including the energy and IAQ impacts, will require field testing and application experience, as well as simulation studies. A number of modeling studies have looked at energy impacts of CO_2 DCV strategies in different building types and different climates (e.g., Brandemuehl and Braun 1999). Other simulation studies have focused on the indoor air quality implications of CO_2 DCV (e.g., Carpenter 1996, Emmerich et al. 1994, Enermodal 1995). The study described in this paper employs an airflow and contaminant dispersal model to investigate the issue of how CO_2 DCV and other ventilation strategies impact indoor air quality and ventilation. In particular, the simulations are focused on how CO_2 DCV impacts the control of non-occupant contaminants, in this case a generic volatile organic compound (VOC), generated at a constant rate to represent contaminants emitted by building materials and furnishings.

These simulations are performed using the airflow and indoor air quality model CONTAMW (Dols and Walton 2002) for six commercial and institutional building spaces. The results are then used to compare ventilation rates, contaminant concentrations and energy associated with ventilation for seven ventilation strategies: constant ventilation volumes specified in ASHRAE Standard 62-2001 and addendum 62n, a theoretical demand control strategy that perfectly tracks occupancy, and four CO_2 DCV strategies with different maximum and minimum flow rates, including one based on California’s Title 24 requirements.

2. DESCRIPTION OF ANALYSIS

The simulations in this study were performed using the multizone network airflow and contaminant dispersal model CONTAMW (Dols and Walton 2002). This model allows one to represent a building as a collection of interconnected zones and then calculates airflow rates induced by weather and ventilation system operation based on air leakage characteristics of the boundaries between zones and pressures and on ventilation system airflows. The user can also enter contaminant source strengths to calculate concentrations over time based on the calculated airflow rates and other mass transport mechanisms (e.g. filtration, deposition, chemical reaction). The latest version of CONTAMW can simulate the performance of controls, in which an airflow rate, fan or damper is controlled based on the contaminant concentration, temperature or pressure in a zone. The simulations described in this report employed this new capability in simple models of the six study spaces as a means of simulating CO_2 DCV.

2.1 Study Spaces

Building models were created in CONTAMW for six different space types. Four of these were generic spaces devised for the purposes of this study: office, conference room, lecture hall and classroom. The two other spaces were based on actual buildings being monitored as part of a larger study on CO_2 DCV being conducted as part of the same CEC-sponsored program that supported this work: portable classroom and playroom in a fast food restaurant. Table 1 summarizes the characteristics of the six spaces including floor area, ceiling height and design occupancy. For the first four spaces, the design occupancy is based on the default values given in ASHRAE Standard 62-2001 (ASHRAE 2001a). Actual dimensions of the two monitored spaces were used to construct models of the portable classroom and fast food playroom, and the occupancies were estimated based on available design information.

Space type	**Floor area m^2 (ft^2)**	**Ceiling height m (ft)**	**Design occupancy # of people**	**Occupant density #/100 m^2 (#/1000 ft^2)**	**Ventilation system operating time**
Office	1000 (10760)	3.0 (9.8)	70	7.0 (6.5)	0600-1900
Conference Room	100 (1076)	3.0 (9.8)	50	50.0 (46.5)	0600-1800
Lecture Hall	100 (1076)	6.0 (19.7)	150	150.0 (139.4)	0800-2100
Classroom	100 (1076)	3.0 (9.8)	35	35.0 (32.5)	0600-1800
Portable classroom	89 (958)	2.6 (8.5)	20	22.5 (20.9)	0700-1700
Fast food restaurant	125 (1346)	5.4 (17.7)	70	56.0 (52.0)	0600-2400

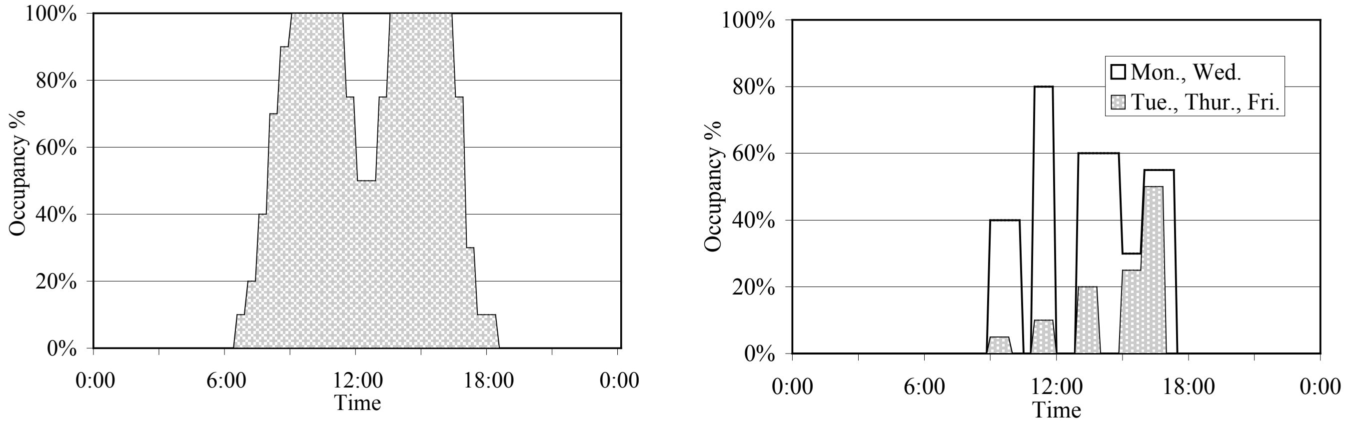
Table 1 Space Characteristics

Each space was modeled as a single zone with a ventilation system that provides outdoor air at a rate determined by the control strategy of interest, as outlined below. Details of the ventilation system equipment were not considered in this study, though they can be important; only the outdoor air intake rate is accounted for in the modeled ventilation systems. The systems are assumed to operate during the times indicated in the last column of Table 1 and to be off at night and during unoccupied periods over the weekends. A constant infiltration rate of 0.1 air changes per hour is assumed to exist in each space at all times, including when the ventilation system is operating. This value was chosen to represent a low infiltration condition that might exist under low wind speeds and moderate outdoor temperatures and result in significant buildup of contaminants before the system is activated.

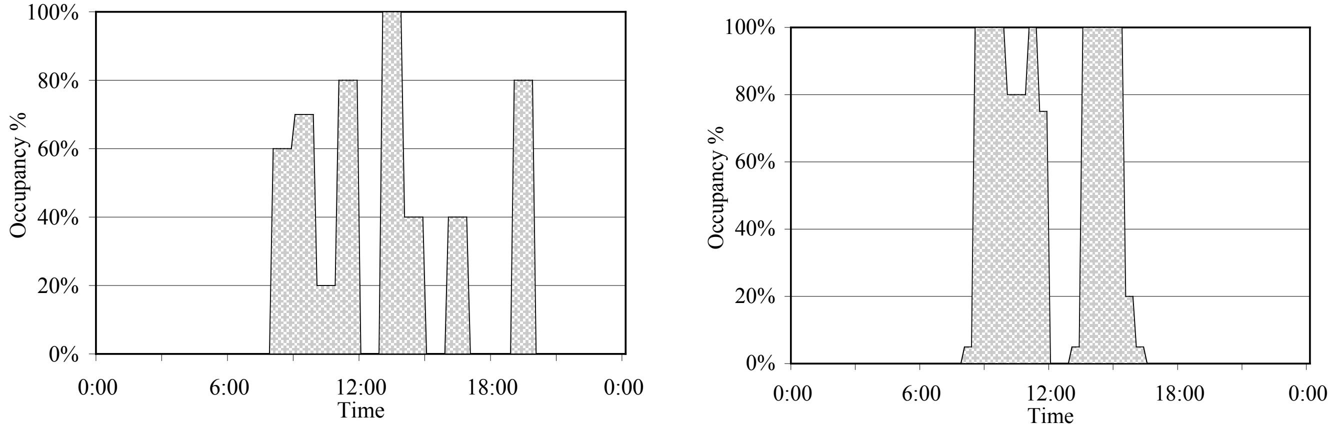
Occupancy profiles

Weekly occupancy schedules for each space are shown in Figure 1. Schedules for the four generic spaces (1a through 1d) were selected to represent realistic usage and to include scenarios that were significantly different from one another in order to test of each control scheme. The Office and Classroom tend to experience long periods at close to their design occupancies. Occupancy changes in the morning and evening are more gradual for the Office, where workers tend to arrive and depart at different times. The Classroom is more densely occupied than the Office, and operates on a more rigid schedule, with the students arriving, departing, and taking lunch at the same time. However, it was assumed that a teacher would arrive early and stay later than the students. In contrast, the Lecture Hall and Conference Room are intermittently occupied. The Lecture Hall schedule is the busier of the two, with more occupied hours in the day, and usually with 50 % or more of the design capacity when the room was occupied. The Conference Room is modeled with two occupancy profiles, with a busier schedule specified for Mondays and Wednesdays. All four of these spaces are assumed to be unoccupied on weekends, and all occupants for these spaces are specified as adults.

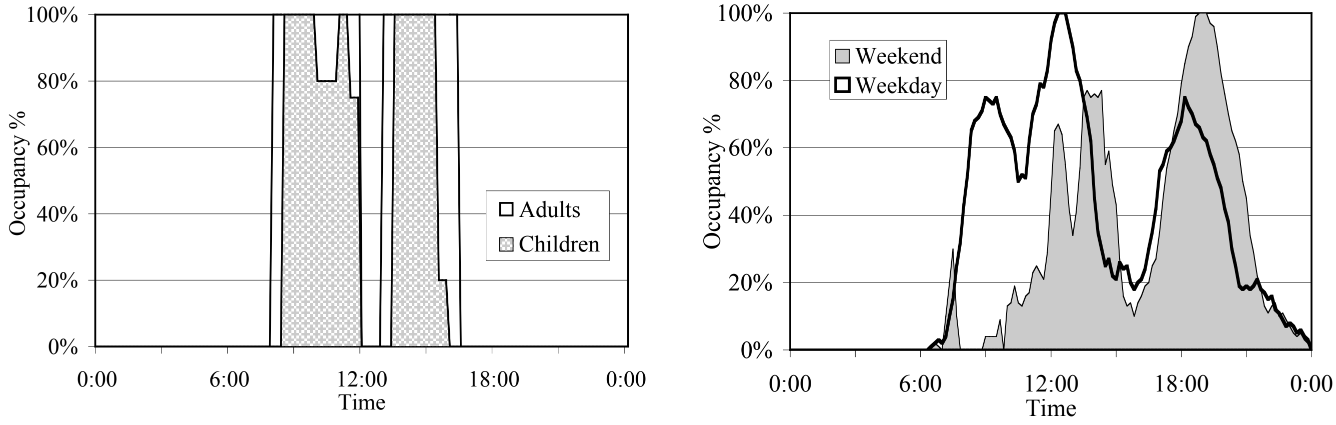
The Portable Classroom was modeled with two adults and eighteen children. The occupancy profile specified for the Classroom is also used here for the children, with different CO_2 generation rates for the adults and children based on body size. The occupancy profiles used for the Fast Food Restaurant simulations are based on actual occupancy data collected in the monitored restaurant. These data were used to develop an occupancy schedule between 0600 to 2400 seven days a week, with different schedules for weekdays and weekends.



(a) Office (b) Conference Room



(c) Lecture Hall (d) Classroom



(e) Portable Classroom (f) Fast food restaurant

Figure 1 Occupancy Schedules

Contaminant generation rates

The simulations accounted for two contaminants, occupant-generated carbon dioxide (CO_2) and a generic volatile organic compound (VOC) intended to represent contaminants from building materials and furnishings. While VOC emissions in buildings are far more complex than the simple approach used here (Levin 1995, Wolkoff 1995), the objective in including VOCs in these simulations was to capture the impact of DCV systems on non-occupant sources that are relatively constant over and time by including a source strength related to the floor area of the space.

In these simulations, CO_2 was generated by adults at a rate of 0.3 L/min•person, which corresponds to an activity level consistent with office work (ASHRAE 2001b). In the Portable Classroom, children were assumed to generate CO_2 at a rate of 0.18 L/min•person, a value based on the body size of a ten year old child. Carbon dioxide generation in the Fast Food Restaurant playroom was modeled as 0.3 L/min•person, a value appropriate for both sedentary adults and small school children at an activity level of 2.5 met (ASTM 2002, EPA 1999). The emission rate for the generic VOC was assumed to be constant at a rate of 0.25 mg/h per m^2 of floor area during unoccupied periods and 0.50 mg/h•m^2 during occupancy. These values are based on limited field measurements of VOC emission rates (Levin 1995). Although actual contaminant generation rates may differ significantly for different building types, there is not sufficient data available to justify varying these rates in this study. Sorption and re-emission of VOCs from surfaces were not modeled in these simulations, and the outdoor concentrations of CO_2 and VOC were assumed to equal 720 mg/m^3 (400 ppm(v)) and 0 mg/m^3 respectively over the entire simulation period.

2.2 Ventilation Rates and Control Approaches

The ventilation rates in the spaces were based on ASHRAE Standard 62-2001, the revision to those rates described earlier (Addendum 62n), and the requirements in California's Title 24 (CEC 2001). Table 2 presents the outdoor air requirements for each space based on 62-2001, addendum 62n, and Title 24. For Standard 62-2001, the outdoor air requirements are presented in L/s•person (cfm/person) followed by the outdoor air intake requirement for the space based on the number of occupants (see Table 1). These outdoor air intake rates for each space are presented in L/s (cfm) and in L/s•m^2 (cfm/ft^2) of floor area. For addendum 62n, the outdoor air requirements are presented as both the people and area rate, which are then combined based on the number of occupants and the floor area of the space given in Table 1. Title 24 requires 7.1 L/s (15 cfm) per person based on the larger of the actual design occupancy or 50% of the exiting density specified by the Uniform Building Code (UBC), with a minimum ventilation rate of 0.76 L/s•m^2 (0.15 cfm/ft^2). Under Title 24, carbon dioxide DCV cannot be used in the Office, since the 0.76 L/s•m^2 (0.15 cfm/ft^2) minimum is larger than 7.1 L/s (15 cfm) for the assumed occupant density. Therefore the outdoor air intake for the Office is based on the floor area rather than the number of people. Also, the assumed occupancy for the Portable Classroom (20 people) is less than 50% of the UBC exiting density, so the maximum flow rate for that case is based on 24 occupants. Note that since the simulations were originally performed using IP units, the ventilation requirements in Table 2 are correct for IP units. The SI values are converted from the IP values, resulting in slight differences relative to the SI values contained in Standard 62-2001, Addendum 62n and Title 24.

For each space type, Table 2 also contains the steady-state CO_2 and VOC concentrations corresponding to the design outdoor air intake rate based on the assumed VOC and CO_2 generation rates. Note that for the Standard 62-2001 ventilation rates, the steady-state CO_2

concentrations range from about 1500 mg/m^3 (900 ppm(v)) to 1900 mg/m^3 (1100 ppm(v)), except in the two cases employing the intermittent occupancy provision of the standard. The VOC concentrations vary more widely, over a range of twenty to one, with the variation due primarily to the variation in the floor area per occupant among the spaces. The VOC levels are all range from less than 0.1 mg/m^3 to 0.2 mg/m^3, with the lowest concentrations in the more densely occupied spaces. Note that these concentrations are on the low end of those reported from field measurements in commercial buildings, which are in this range and even higher in non-problem buildings (Anderson et al. 1997, Brown et al. 1994, Daisey et al. 1994, Hadwen et al. 1997, Wolkoff 1995). Note that the concentrations in Table 2 are all steady-state values, i.e., the values that would eventually exist if the emission rate and ventilation rate were maintained long enough for steady-state conditions to be achieved. However, depending on the occupancy and ventilation schedules, steady-state conditions will not necessarily occur in these spaces.

The outdoor air ventilation rates for the six spaces based on Addendum 62n tend to be lower than those based on 62-2001, particularly in the more densely occupied spaces (Conference Room, Lecture Hall and Restaurant). In fact, part of the reason for the changes in this addendum was the concern that the existing rates in the standard were larger than necessary in densely occupied spaces due to “overcounting” of emissions from floor area-related contaminants. The ventilation rate in the Portable Classroom is slightly higher under 62n based on it having a lower occupancy density than assumed in Standard 62-2001. The lower ventilation rates under the addendum generally result in higher steady-state CO_2 levels, particularly in the densely occupied spaces. Most of the values are still in the range of 1800 mg/m^3 (1000 ppm(v)), but the two most densely occupied spaces (Conference Room and Lecture Hall) are closer to 3600 mg/m^3 (2000 ppm(v)). The VOC levels for the 62n rates are generally higher than those based on 62-2001, with the largest increases again seen in the densely occupied spaces. However, the VOC levels are still range from less than 0.1 mg/m^3 to 0.3 mg/m^3, again on the low end of concentrations measured in the field. Again, these are all steady-state concentrations, which may not necessarily occur in these spaces given the occupancy schedules. Also, these steady-state VOC concentrations are based on the ventilation rates and source strengths assumed to exist during occupied periods and neglect any impacts of higher concentrations that might occur overnight when the system is off.

For Title 24 the steady-state CO_2 levels are all approximately 2000 mg/m^3 (1100 ppm(v)), with lower levels in the Office and the Portable Classroom. In the office, the lower concentration results from its ventilation requirement under CO_2 DCV being based on 0.76 L/s•m^2 (0.15 cfm/ft^2), which is higher than 7.1 L/s (15 cfm) per person. The Portable Classroom outdoor air intake rate is based on 24 occupants rather than the actual 20 occupants based on the Title 24 requirement to assume no less than 50 % of the UBC exiting density. The steady-state VOC concentrations are similar to those seen for Standard 62-2001 and Addendum 62n.

Standard 62-2001

		Outdoor air intake		Steady-state concentration	
Space type	Outdoor air requirement L/s (cfm) per person	L/s (cfm)	L/s•m^2 (cfm/ft^2)	CO$_2$ mg/m^3 (ppm(v))	VOC mg/m^3
Office	9.4 (20)	661 (1400)	0.7 (0.13)	1674 (930)	0.21
Conference Room	9.4 (20)	472 (1000)	4.7 (0.93)	1674 (930)	0.03
Lecture Hall	7.1 (15)	1062 (2250)	10.6 (2.09)	1991 (1106)	0.01
Classroom	7.1 (15)	248 (525)	2.5 (0.49)	1991 (1106)	0.06
Portable classroom	7.1 (15)	142 (300)	1.6 (0.31)	1532 (851)	0.09
Fast food restaurant	9.4 (20)	661(1400)	5.3 (1.04)	1674 (930)	0.03
Conference room*	9.4 (20)	236 (500)	2.4 (0.47)	2626 (1459)	0.06
Lecture Hall*	7.1 (15)	531 (1125)	5.3 (1.05)	3262 (1812)	0.03

* Under intermittent occupancy provision of Standard 62-2001

Addendum 62n

		Outdoor air intake		Steady-state concentration	
Space type	Outdoor air requirement L/s (cfm) per person/ L/s•m^2 (cfm/ft^2)	L/s (cfm)	L/s•m^2 (cfm/ft^2)	CO$_2$ mg/m^3 (ppm(v))	VOC mg/m^3
Office	2.4/0.3 (5.0/0.06)	470 (996)	0.5 (0.09)	2061 (1145)	0.30
Conference Room	2.4/0.3 (5.0/0.06)	149 (315)	1.5 (0.29)	3740 (2078)	0.09
Lecture Hall	3.5/0.3 (7.5/0.06)	562 (1190)	5.6 (1.11)	3123 (1735)	0.03
Classroom	4.7/0.6 (10/0.12)	226 (479)	2.2 (0.44)	2113 (1174)	0.06
Portable classroom	4.7/0.6 (10/0.12)	149 (315)	1.7 (0.33)	1494 (830)	0.08
Fast food restaurant	3.5/0.9 (7.5/0.18)	362 (767)	2.9 (0.57)	2461 (1367)	0.05

Title 24

		Outdoor air intake		Steady-state concentration	
Space type	Outdoor air requirement	L/s (cfm)	L/s•m^2 (cfm/ft^2)	CO$_2$ mg/m^3 (ppm(v))	VOC mg/m^3
Office	0.76 L/s•m^2 (0.15 cfm/ft^2)	762 (1614)	0.75 (0.15)	1546 (859)	0.18
Conference Room	7.1 L/s (15 cfm) per person	354 (750)	3.5 (0.70)	1991 (1106)	0.04
Lecture Hall	7.1 L/s (15 cfm) per person	1062 (2250)	10.6 (2.09)	1991 (1106)	0.01
Classroom	7.1 L/s (15 cfm) per person	248 (525)	2.5 (0.49)	1991 (1106)	0.06
Portable classroom	7.1 L/s (15 cfm) per person	170 (360)	1.9 (0.38)	1399 (777)	0.07
Fast food restaurant	7.1 L/s (15 cfm) per person	495 (1050)	4.0 (0.78)	1991 (1106)	0.04

Table 2 Design Ventilation Rates and Steady-State Contaminant Levels during Occupancy

Seven ventilation control scenarios were simulated in the six spaces, with one additional scenario applied to two of them. The first three scenarios, based on ASHRAE Standard 62, serve as reference cases for comparing the DCV options. They are:

62/2001: Constant outdoor air intake rates based on ASHRAE Standard 62-2001 and the design occupancy values in Table 1.

62tracking: Outdoor air intake rates that track occupancy (as depicted in Figure 1) perfectly using the ASHRAE Standard 62-2001 rates, i.e., the intake rate always equals the number of occupants times the per person ventilation requirement.

62/Int: Outdoor air intake rate based on 50 % of peak occupancy using the intermittent occupancy approach in the standard (only applied to the Conference Room and Lecture Hall).

Two cases employing CO_2 DCV using the Standard 62-2001 rates were also studied:

C-ZeroMin: Maximum ventilation rate based on ASHRAE Standard 62-2001; minimum ventilation rate equal to zero.

C-25%Min: Maximum ventilation rate based on ASHRAE Standard 62-2001; minimum ventilation rate equal to 25 % of the maximum.

In addition, two cases were studied based on the revision of the Ventilation Rate Procedure in the standard, so-called addendum 62n:

62n: Constant outdoor air intake rates based on addendum 62n and the design occupancy values from Table 1.

C-62nAreaMin: CO_2 DCV control with the maximum ventilation rate based on the design occupancy and the requirements in addendum 62n; minimum ventilation rate equal to the "area" requirement times the floor area of the space.

Finally, one case followed the requirements of California's Title 24:

C-T24: CO_2 DCV control with the maximum ventilation rate based on the requirement for 7.1 L/s (15 cfm) person in these spaces, using the larger of the design occupancy or 50 % of the UBC exiting density. The minimum ventilation rate is based on 0.76 L/s•m^2 (0.15 cfm/ft^2). In the case of the office, the ventilation rate is constant at this minimum level because the per person requirement results in a ventilation rate that is lower than this value.

For the reference cases and the 62n case, it was not necessary to model outdoor air intake controls. In the simulations, the ventilation system was simply scheduled to turn on and off per the operating schedules described earlier. In the case of 62tracking, in which the outdoor air intake rate was "controlled" to track occupancy perfectly, the fan was set to follow the same schedule as the occupancy. For the cases in which CO_2 control was implemented, the control simulation capabilities of CONTAMW were employed. A proportional control algorithm based on previously published descriptions was used (Schell, et al. 1998, Schell and Int-Hout 2001). The proportional controllers were specified to modulate the ventilation rate between the minimum and maximum rates with a linear response to CO_2 concentration based on the output *O* described below. The lower limit of this range was selected to be 90 mg/m^3 (50 ppm(v)) higher than the outdoor level, and the upper CO_2 limit was set at the equilibrium concentration corresponding to the design occupancy and design ventilation rate under steady conditions C_{eq}. For the Title 24 case, the upper CO_2 limit was set to 1440 mg/m^3 (800 ppm(v)) for all cases, with constant flow at the maximum ventilation rate delivered at all concentrations above this level. The CONTAMW proportional control algorithm calculates the output *O* according to the following relationship,

$$O = I \, x \, K_p \tag{1}$$

where I is the controller input and K_p is a constant. In this control strategy the controller input is the indoor CO_2 concentration minus 810 mg/m^3 (450 ppm(v)), and K_p defined as,

$$K_p = 1 / [C_{eq} - 450 \, ppm(v)] \tag{2}$$

Other control algorithms have been proposed and employed for CO_2 DCV, such as proportional-integral control.

2.3 Airflow and contaminant analysis

Each of the cases was simulated in the six spaces for a period of 7 days. The simulations were performed using a 5 min time step and yielded a CO_2 and VOC concentration at each time step. In the case of the DCV systems, the simulations also yielded a ventilation rate. These ventilation data were analyzed to yield the average ventilation rate during the occupancy period. The CO_2 concentration data were analyzed to yield the average concentration over the occupancy period and the peak hourly average during occupancy. The VOC data were also analyzed to determine the average concentration during occupancy, plus the peak concentration. Plots of CO_2 and VOC concentrations during the simulation period are presented in the results section.

2.4 Energy analysis

In order to compare the energy consumption associated with the different ventilation control cases, a simplified approach was used to estimate the heating and cooling loads associated with conditioning the ventilation air to the indoor conditions based on the sensible and latent heat capacity of the outdoor air relative to the indoor air. Therefore, the energy analysis accounts for only the load due to ventilation air, and not the energy required to meet that load, which depends on the type of system used to meet that load. Economizer operation is, however, taken into account by not including any cooling energy consumed when operating in this mode. Also, no energy consumption is assessed when the outdoor air temperature is between the heating balance point and the space temperature

Determination of heating balance point temperature

The balance point temperature was estimated using a simplified steady-state energy balance in which the heat transferred out of the structure equals the heat transferred in via airflows and internal gains:

$$(\Sigma UA + QC_p)\, T_o + q = (\Sigma UA + QC_p)\, T_i \qquad (3)$$

where,

ΣUA = building envelope thermal conductance
Q = mass flow rate of ventilation air
C_p = specific heat of air
T_o = outdoor temperature
T_i = indoor temperature
q = internal heat gains

The heating balance point temperature is the outdoor temperature at which internal heat gains are equal to the heat loss rate at a given ventilation rate and indoor temperature, T_i. Heating is required below this temperature, and internal gains maintain the building at the heating setpoint above this temperature. The heating balance point, T_{hbp}, can be defined as:

$$T_{hbp} = T_i - q / (\Sigma UA + QC_p) \qquad (4)$$

The thermal conductance term (ΣUA) is often much smaller than the ventilation flow term in equation (4) for commercial buildings, and is sometimes neglected. However, since some of the airflow control strategies allowed the airflow to occasionally go to zero, it was maintained for this analysis. However, the accuracy of the thermal conductance term is not critical, since the QC_p term is usually much larger than the UA term. The value of ΣUA was estimated based on

ASHRAE Standard 90.1 envelope requirements (ANSI/ASHRAE/IESNA 1999). During the few times when the ventilation flow rate does approach zero, the heating balance point is so low that it was not reached in any of the climates investigated.

Table 3 shows the internal heat gain used for each space, which were estimated using data published for nonresidential cooling and heating load calculations by ASHRAE (2001b). Occupant heat gains were based on the average modeled occupancy during the occupied period and assumed occupant activity levels. Heat gain from lighting was estimated using the installed lighting load from ASHRAE Standard 90.1 (ANSI/ASHRAE/IESNA 1999), adjusted for usage and allowance factors. Heat gain from 80 computers was included for the office.

	Occupants	**Lighting**	**Computers**	**Total**
Space	W/m^2	W/m^2	W/m^2	W/m^2
Office	4.9	12.1	10.0	27.0
Conference Room	9.8	6.4	0.0	16.2
Lecture Hall	42.0	9.3	0.0	51.3
Classroom	16.1	9.3	0.0	25.4
Portable Classroom	7.8	9.3	0.0	17.1
Fast Food Restaurant	17.3	20.1	0.0	37.3

Table 3 Internal Heat Gains Used to Estimate Balance Point

The weekly CONTAM simulations, repeated for an entire year, were used to determine the ventilation mass flow rate in equation (4). And because the heating balance point depends on this flow rate, it was calculated individually for each hour of the year.

Heating load

Based on the estimated heating balance point temperature, the heating load associated with ventilation was calculated for each hour in which the outdoor temperature was below the heating balance point using the relationship:

$$q_{heating} = QC_p\,(T_i - T_o) \qquad (5)$$

where,

$q_{heating}$ = heating load
Q = mass flow rate of ventilation air
C_p = specific heat of air
T_o = outdoor temperature
T_i = indoor temperature (assumed 22 ºC year round)

Cooling load

When the outdoor temperature is greater than the indoor temperature, the additional sensible cooling load $q_{cooling}$ associated with the ventilation air can be calculated from the relationship:

$$q_{cooling} = QC_p\,(T_o - T_i) \qquad (6)$$

Whether or not a latent cooling load exists depends, to some extent, on the latent loads as well as the degree of humidity control that can be achieved by the means of thermal conditioning in the space. For this simplified model, it was assumed that the thermal control strategy was capable of maintaining a maximum indoor relative humidity of 60 %. Therefore, when the outdoor humidity ratio exceeds this humidity ratio upper limit, a latent load associated with ventilation is assessed:

$$q_{latent} = Q\,h_{fg}\,(W_o - W_{limit}) \qquad (7)$$

where,

q_{latent} = latent cooling load
Q = mass flow rate of ventilation air
h_{fg} = latent heat capacity of moist air
W_o = outdoor humidity ratio
W_{limit} = indoor humidity ratio (defined at 60 % relative humidity at 22 ºC)

The energy calculations assume that each space operates with a return air temperature economizer that uses outdoor air for cooling. Under this strategy the system provides 100 % outdoor air when the outdoor dry bulb temperature is between the supply air temperature and the indoor temperature. Some mechanical cooling will be required under these conditions, but it will be less than would be needed if indoor air was recirculated. When the outdoor temperature is above the heating balance point but below the system supply temperature, the economizer strategy mixes return air with a volume of outdoor air greater than that needed for ventilation, and neither cooling nor heating is required. In both of these cases, thermal conditioning and control, not the ventilation control strategy, dictate the amount of outdoor air supplied to the spaces. Since our approach is intended to determine the heating and cooling loads associated with ventilation, cooling energy consumed in this mode is not included in the reported values.

The heating, cooling, and latent loads associated with ventilation were calculated for every hour during which the ventilation system was assumed to be operating. These were then summed for each case over an entire year of weather data for the six cities identified below.

Climates analyzed

Based on the methodology outlined above, the energy consumption was estimated for four California climates (Bakersfield, Los Angeles, Sacramento, and San Francisco) selected to cover a range of coastal and inland climates. As points of reference, Miami (hot and humid) and Minneapolis (cold) were also analyzed. These energy estimates employed TMY2 weather data (Marion and Urban 1995), except for Sacramento and Miami for which WYEC data (ASHRAE 1997) was used. Table 3 summarizes the weather data for these six climates.

City	Heating degree days °C (°F)	Cooling degree days °C (°F)
Bakersfield	1213 (2183)	1210 (2178)
Los Angeles	1010 (1816)	341 (614)
Sacramento	1579 (2842)	643 (1157)
San Francisco	1690 (3042)	60 (108)
Miami	114 (205)	2243 (4037)
Minneapolis	4532 (8158)	325 (585)

Table 4 Summary of Six Climates Analyzed (Knapp et al. 1980)

3. RESULTS

This section presents the results of the simulations for the six space types, seven ventilation control approaches and six climates. These results are presented separately for the ventilation rates, CO_2 and VOC contaminant concentrations, and energy loads.

3.1 Ventilation Rates

The ventilation rates for the different space types and control strategies are summarized in Table 5. Note that these rates are inputs to the contaminant simulations for three of the cases (62/2001, 62 tracking and 62n), as well as 62/Int when relevant, but are calculated during the simulations for the four DCV cases (C-ZeroMin, C-25%Min, C-62nMinArea and C-T24). Also note that the intermittent occupancy case is only applied to the Conference Room and Lecture Hall. Also, while the Title 24 case is thought of as DCV, in the case of the Office it is in fact a constant ventilation rate based on the minimum outdoor air requirement of 0.76 L/s•m^2 (0.15 cfm/ft^2).

For each space and control strategy, Table 5 contains the average, minimum and maximum outdoor air intake during occupancy in units of airflow rate per person L/s•person (cfm/person). Also, in the first column, the table presents the per person design value for outdoor air intake for Standard 62-2001, addendum 62n and Title 24. The calculations were initially performed in IP units and converted to SI units. Therefore, some of the SI values are slightly different from those that appear in Standard 62, addendum 62n and Title 24. The last column of the table contains the minimum and maximum per person outdoor air intake during periods of time when the space is at its maximum occupancy level. For some spaces (e.g., Office) the space is at maximum occupancy for many hours, while for other spaces (e.g., Fast Food) maximum occupancy occurs for only short periods of time. Note that the Conference Room is never at its design occupancy of 50 people, but rather has a maximum occupancy of 40.

The maximum rates during occupancy in Table 5, for all but the 62tracking case, are well above the relevant requirements of Standard 62, 62n or Title24. This is particularly true for cases 62/2001 and 62n in which the design outdoor air intake is in effect whenever the system operates, which results in high per person rates when the occupancy is low. For the 62tracking case, the averages, minimums and maximums are all equal to the Standard 62 requirement as expected, except in the Portable Classroom because the 62tracking case is actually based on the CO_2 generation rates of the occupants. (Since different CO_2 generation rates are used for the adults and children in that space, there is some variation in the per person rates based on whether the space is occupied by only the adults or by the whole class.) The minimum per person rate for the case of C-ZeroMin is always zero, since the intake is at its minimum position (zero intake) until the CO_2 levels build-up after the space has been occupied for some time. The other CO_2 DCV cases also have minimum per person rates below the rate required by the standard, as the indoor CO_2 levels are too low at the start of occupancy for the CO_2 controls to induce outdoor air intake. However, these low rates are temporary and not unexpected.

Figures 2 through 7 are plots of the total ventilation rates, including infiltration, for each of the spaces and ventilation control approaches over a period of one or two days. The one-day plots all contain data for a Friday, to capture the impact of any CO_2 buildup over the week in cases where the assumed infiltration rate of 0.1 h^{-1} is not sufficient to bring the indoor CO_2 level down to the outdoor level overnight. For the CO_2 control cases, this residual CO_2 leads to a low level of ventilation early in the morning. For the spaces with occupancy patterns that vary by day of the week, two days are presented in the corresponding figure. Specifically, Figure 3 presents the ventilation rates for Wednesday and Thursday in the Conference Room, and Figure 6 presents

Friday and Saturday for the Fast Food Restaurant. In all the figures, the 62-2001 and 62n cases are horizontal lines indicating constant ventilation rates when the system operates. The Title 24 case C-T24 results in a constant intake rate for the office space as discussed earlier. The intermittent occupancy cases (62-Int) in the Conference Room and the Lecture Hall, Figures 3 and 4 respectively, also exhibit constant ventilation rates. The 62tracking case appears as a solid black line in all the figures, with the ventilation rate corresponding to the occupancy schedule of the given space. The four control cases (C-ZeroMin, C25%Min, C-62nAreaMin and C-T24) exhibit more variation as the controls respond to the indoor CO_2 level. They generally start each day low relative to the constant ventilation rate cases, with the ventilation rates increasing as the indoor CO_2 levels increase.

Referring to Table 5, the results for the Office exhibit a number of trends that are also reflected in most of the other spaces. The average per-person outdoor air intake rate is the second highest for the 62/2001 case in which the intake rate is always equal to 9.4 L/s (20 cfm) times the maximum number of occupants. Under low occupancy, the constant intake rate is divided by a relatively small number of people, yielding per person ventilation rates with a maximum value of 94 L/s (200 cfm). The lowest average intake rate is for 62tracking, in which the system always brings in 9.4 L/s (20 cfm) per person times the number of people in the space. The 62n rate is also constant during system operation, but at a lower value than 62/2001, resulting in a lower average ventilation rate but still yielding high maximum values when occupancy is low. The C-T24 case has the highest rates in the Office based on the minimum requirement. Other than 62tracking, all the ventilation strategies have high per person intake rates at low occupancy relative to the design values. The control approaches based on the Standard 62 rates (C-ZeroMin and C-25%Min) both have average ventilation rates higher than 62tracking. Therefore, while these CO_2 control strategies may have lower ventilation rates during periods of the day, overall they provide more ventilation air than a “perfect” control system, presumably a desirable and conservative outcome from an indoor air quality perspective.

Figure 2 is a plot of the total outdoor air ventilation rate (intake plus infiltration) for a single day in the Office. Note that the two CO_2 control strategies using the Standard 62 rates, C-25%Min and C-ZeroMin, track the idealized case of 62tracking fairly well, with some “underventilation” early in the day and some “overventilation” after occupancy has peaked and towards the end of the day. However, one could argue that one would desire overventilation at these times to “flush out” residual contaminants and that one could tolerate some underventilation early in the day before contaminants have built up. However, overventilation late in the workday can have an energy penalty in hot weather. The use of the terms underventilation and overventilation are only relative to the rates required by the standard or addendum (design values). The C-25%Min case is more conservative, in that it starts the day with higher ventilation rates relative to the 62tracking and 62-ZeroMin cases. The C-62nAreaMin case is even more conservative in the early part of the day, based on its higher minimum ventilation rate, but it does not provide as much ventilation later in the day as the other DCV cases.

	Outdoor Air Intake Rate (neglecting infiltration) L/s•person (cfm/person)				
	Design value	**During Occupancy**			**Min/Max at maximum occupancy**
		Average	**Minimum**	**Maximum**	
Office					
62/2001	9.4 (20.0)	24.0 (50.9)	9.4 (20.0)	94.0 (200.0)	9.4/9.4 (20.0/20.0)
62tracking	--	9.4 (20.0)	9.4 (20.0)	9.4 (20.0)	9.4/9.4 (20.0/20.0)
C-ZeroMin	--	12.1 (25.7)	0 (0)	65.0 (137.8)	6.1/8.9 (12.9/18.8)
C-25%Min	--	14.7 (31.2)	5.0 (10.5)	70.9 (150.3)	6.6/9.0 (13.9/19.0)
62n	6.8 (14.4)	16.3 (34.6)	6.4 (13.6)	64.1 (135.7)	6.4/6.4 (13.6/13.6)
C-62nAreaMin	--	13.2 (27.9)	5.1 (10.7)	56.9 (120.6)	5.1/6.2 (10.7/13.1)
C-T24	10.8 (23.1)	27.8 (58.8)	10.9 (23.1)	108.9 (230.8)	10.9/10.9 (23.1/23.1)
Conference Room					
62/2001	9.4 (20.0)	49.4 (104.7)	11.8 (25.0)	188.9 (400.1)	11.8/11.8 (25.0/25.0)
62tracking	--	9.4 (20.0)	9.4 (20.0)	9.4 (20.0)	9.4/9.4 (20.0/20.0)
62/Int	--	24.7 (52.4)	5.9 (12.5)	94 (200.0)	5.9/5.9 (12.5/12.5)
C-ZeroMin	--	13.2 (28.0)	0 (0)	26.3 (55.8)	2.0/10.4 (4.2/22.1)
C-25%Min	--	19.7 (41.7)	3.7 (7.9)	53.4 (113.1)	3.7/10.6 (7.9/22.5)
62n	3.9 (8.2)	15.3 (32.5)	3.7 (7.8)	58.5 (124.0)	3.7/3.7 (7.8/7.8)
C-62nAreaMin	--	5.2 (11.0)	1.4 (3.0)	13.4 (28.3)	1.6/3.1 (3.4/6.5)
C-T24	7.1 (15.0)	17.0(36.0)	3.1 (6.6)	42.7 (90.5)	3.2/8.9 (6.8/18.8)
Lecture Hall					
62/2001	7.1 (15.0)	14.7 (31.1)	7.1 (15.0)	35.4 (75.0)	7.1/7.1 (15/15)
62tracking	--	7.1 (15.0)	7.1 (15.0)	7.1 (15.0)	7.1/7.1 (15/15)
62/Int	--	7.4 (15.6)	3.5 (7.5)	17.7 (37.5)	3.5/3.5 (7.5/7.5)
C-ZeroMin	--	10.1 (21.4)	0 (0)	31.6 (67.0)	0.8/7.1 (1.8/15.0)
C-25%Min	--	10.8 (22.9)	2.0 (4.3)	32.1 (68.1)	2.0/7.1 (4.3/15.0)
62n	3.8 (8.0)	7.8 (16.6)	3.8 (8.0)	18.9(40.0)	3.8/3.8 (8.0/8.0)
C-62nAreaMin	--	5.3 (11.2)	0.3 (0.7)	16.5 (35.0)	0.9/3.8 (1.9/8.0)
C-T24	7.1 (15.0)	12.8 (27.1)	0.8 (1.8)	35.4 (75.0)	1.3/7.1 (2.7/15.0)
Classroom					
62/2001	7.1 (15.0)	35.9 (76.1)	7.0 (14.9)	140.3 (297.2)	7.0/7.0 (14.9/14.9)
62tracking		7.0 (14.9)	7.0 (14.9)	7.0 (14.9)	7.0/7.0 (14.9/14.9)
C-ZeroMin		12.1 (25.6)	0 (0)	71.4 (151.2)	0.2/6.9 (0.4/14.7)
C-25%Min		17.1 (36.3)	1.8 (3.8)	84.9 (179.8)	1.8/6.9 (3.8/14.7)
62n	6.7 (14.2)	32.1 (68.1)	6.3 (13.3)	125.6 (266.1)	6.3/6.3 (13.3/13.3)
C-62nAreaMin		15.6 (33.0)	1.6 (3.4)	77.9 (165.0)	1.6/6.2 (3.4/13.1)
C-T24	7.1 (15.0)	20.2 (42.7)	2.2 (4.6)	111.6 (236.5)	2.2/7.0 (4.6/14.9)
Portable Classroom					
62/2001	7.1 (15.0)	21.2 (44.9)	7.0 (14.9)	70.1 (148.6)	7.0/7.0 (14.9/14.9)
62tracking		7.9 (16.7)	7.0 (14.9)	10.9 (23.1)	7.0/7.0 (14.9/14.9)
C-ZeroMin		9.7 (20.6)	0 (0)	43.2 (91.6)	0.5/6.9 (1.0/14.6)
C-25%Min		12.0 (25.4)	1.9 (4.1)	48.4 (102.5)	1.9/6.9 (4.1/14.6)
62n	7.7 (16.2)	21.7 (45.9)	7.2 (15.2)	71.7 (152.1)	7.2/7.2 (15.2/15.2)
C-62nAreaMin		13.3 (28.1)	2.6 (5.6)	51.6 (109.4)	2.6/7.1 (5.6/15.0)
C-T24	8.5 (18.0)	16.0 (33.9)	3.6 (7.6)	60.4 (127.9)	3.6/8.4 (7.6/17.7)
Fast Food					
62/2001	9.4 (20.0)	65.2 (138.1)	9.4 (20.0)	944.0 (2000.0)	9.4/9.4 (20.0/20.0)
62tracking		9.4 (20.0)	9.4 (20.0)	9.4 (20.0)	9.4/9.4 (20.0/20.0)
C-ZeroMin		16.4 (34.8)	0 (0)	87.0 (184.4)	9.2/9.3 (19.5/19.8)
C-25%Min		26.2 (55.5)	9.0 (19.0)	236.1 (500.1)	9.2/9.3 (19.5/19.8)
62n	5.1 (10.8)	35.3 (74.7)	5.1 (10.8)	510.7 (1082.0)	5.1/5.1 (10.8/10.8)
C-62nAreaMin		15.9 (33.6)	4.5 (9.6)	151.8 (321.6)	4.8/5.0 (10.1/10.5)
C-T24	7.1 (15.0)	21.5 (45.5)	7.1 (15.0)	136.2 (288.5)	7.1/7.1 (15.0/15.0)

Table 5 Summary of Ventilation Rates

The Conference Room ventilation results are also presented in Table 5, with the additional case of 62/Int, which implements the intermittent occupancy provision of Standard 62-2001. The highest average intake rate is for 62/2001. Note that the conference room is never occupied at its design value of 50 occupants; the maximum is 40 in these simulations, and this value only occurs for a few hours on Mondays and Wednesdays. Based on the lower and more variable occupancy pattern relative to the Office, the maximum ventilation rates for the CO_2 control approaches are not as high relative to 62-2001 as in the Office. In the Office control cases, the ventilation rates continue to increase over several hours of high occupancy. However, in the Conference Room the occupancy drops before the CO_2 levels get as high, and the ventilation rates are lower on average. Figure 3 presents the Conference Room ventilation rates for Wednesday and Thursday of the simulation period. The most significant difference from the Office results in Figure 2 is seen for the CO_2 control cases that “overshoot” the 62tracking case. This “overshooting” occurs during the short periods of elevated occupancy because these peak occupancy levels are below the design value and the maximum ventilation rate in the CO_2 control algorithm is based on the design occupancy. The Conference Room in fact never achieves the design occupancy, and therefore this overshoot occurs for all the occupancy peaks.

The Lecture Hall results in Table 5 are similar to those for the Conference Room except all the rates are lower given the lower design ventilation rates. Also, the Lecture Hall does attain its design occupancy level, even if only briefly. The Lecture Hall ventilation rates are plotted in Figure 4 and also exhibit the “overshoot” relative to the 62tracking case that is seen in the Conference Room. However, the occupancy peak that occurs after lunch is at the design occupancy level and therefore no overshoot is seen here.

The results for the Classroom and Portable Classroom are similar, with some differences seen due to the lower occupancy density and lower average CO_2 generation rate in the Portable Classroom. These differences generally result in lower per person ventilation rates. The ventilation rates plotted in Figures 5 and 6 for the two spaces exhibit very similar patterns, with the values lower in the Portable Classroom. Note that the C-T24 case has the highest ventilation rates of the control cases in both classrooms, notably so in the Portable Classroom.

The Fast Food Restaurant has an extremely variable occupancy pattern in which the design occupancy pattern is only achieved briefly once during each day. Therefore, the ratio of the average and maximum per person ventilation rates to the design value for the 62/2001 and 62n case are highest for this space. The ventilation rates for Friday and Saturday in this space are plotted in Figure 7.

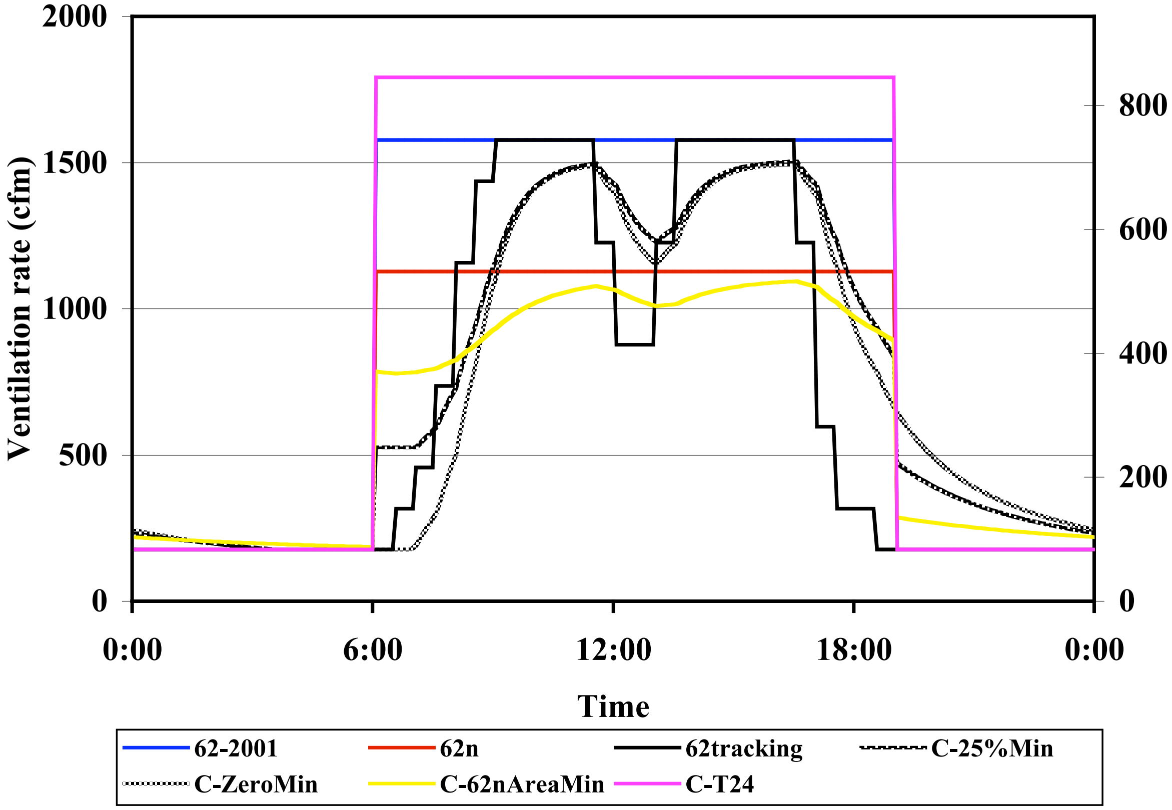


Figure 2 Office Ventilation Rates during Weekday (Friday)

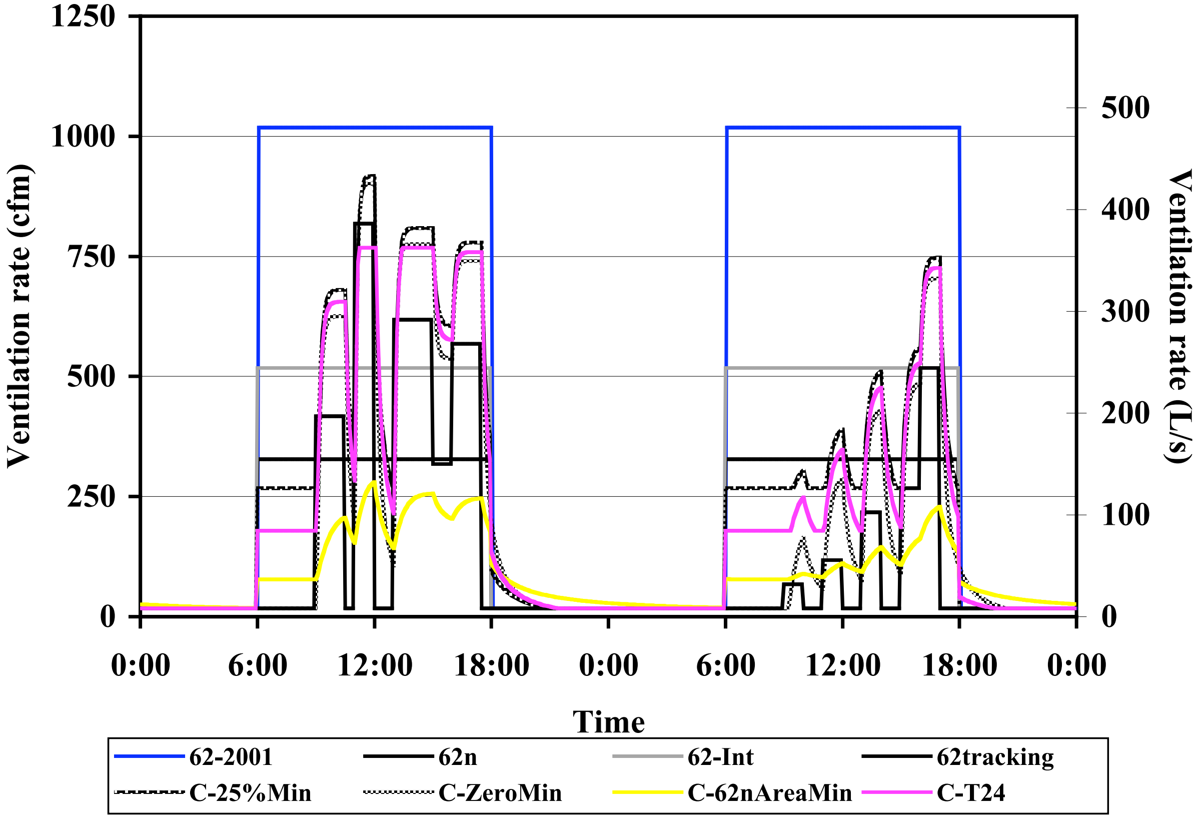


Figure 3 Conference Room Ventilation Rates during Week (Wednesday and Thursday)

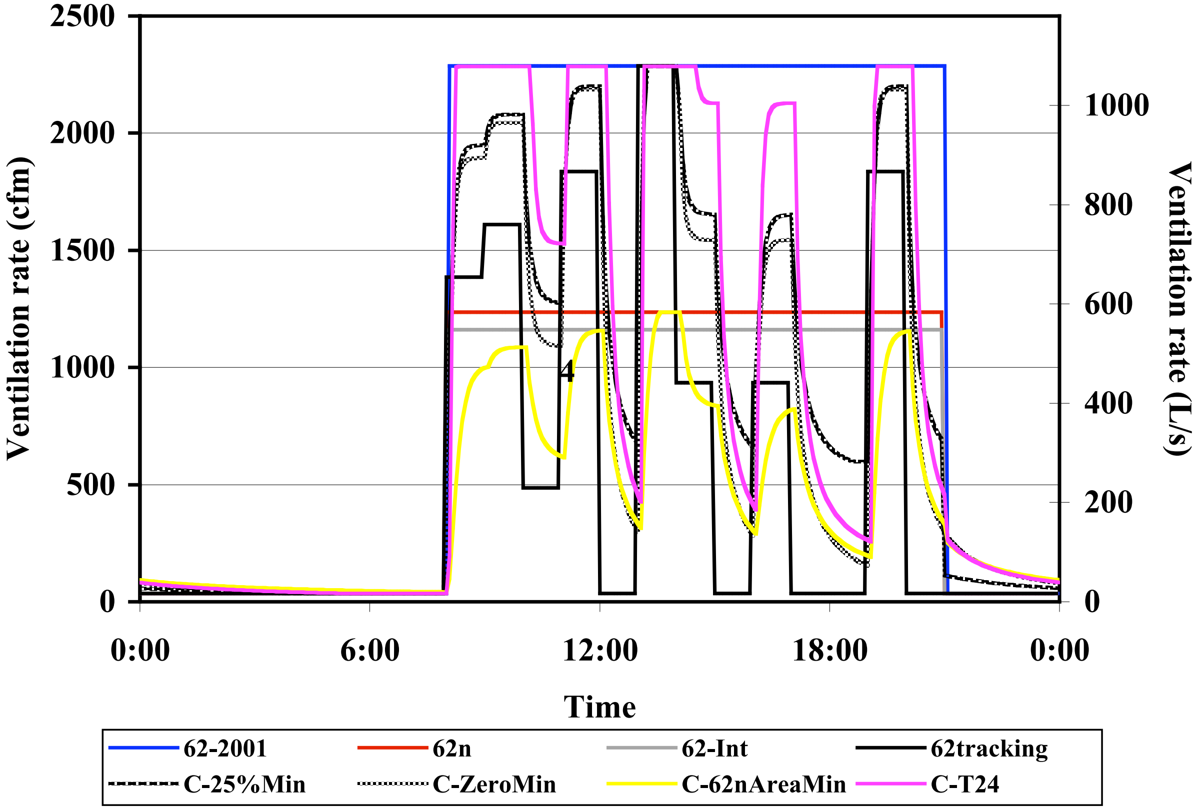


Figure 4 Lecture Hall Ventilation Rates during Week (Friday)

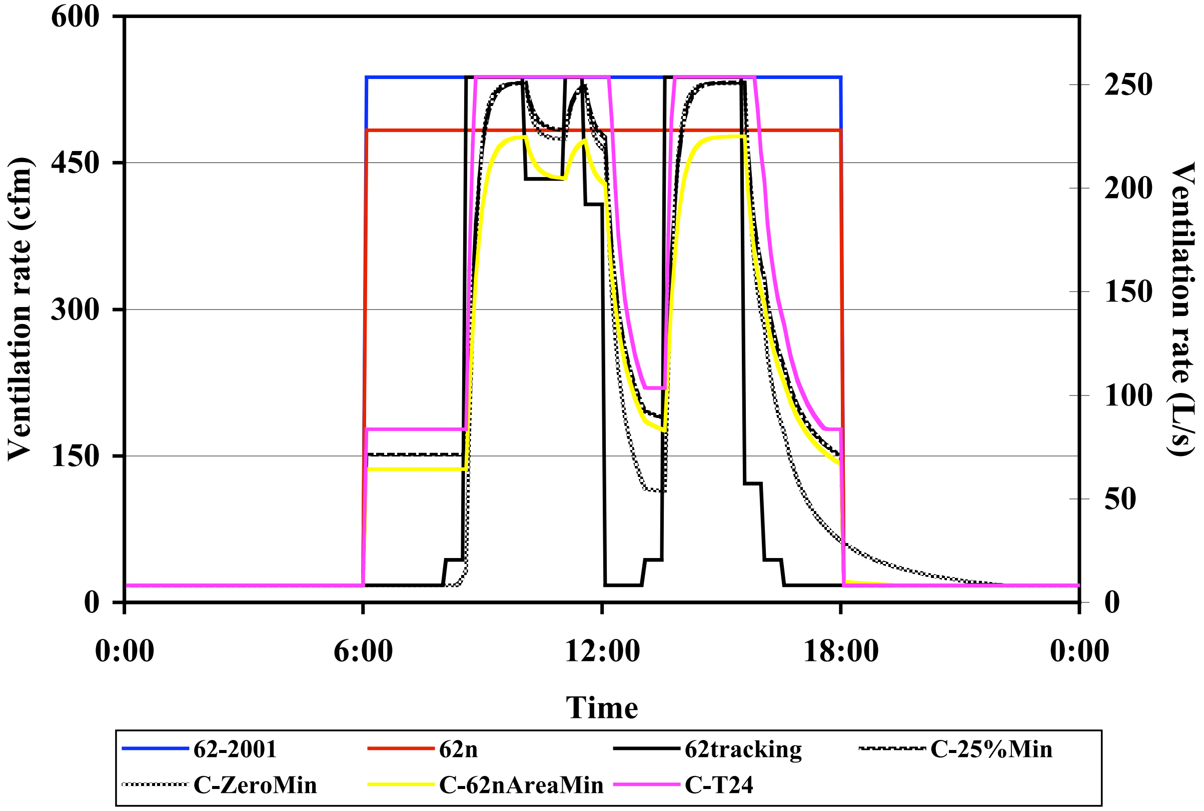


Figure 5 Classroom Ventilation Rates during Week (Friday)

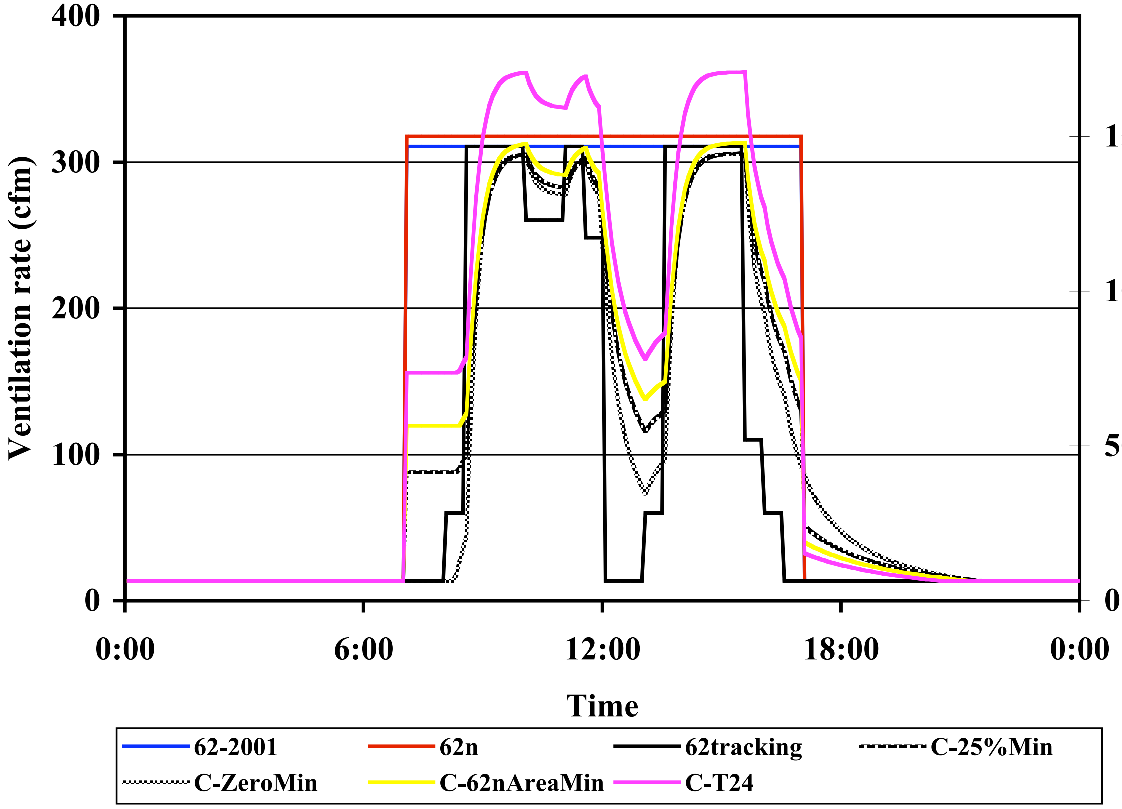


Figure 6 Portable Classroom Ventilation Rates during Week (Friday)

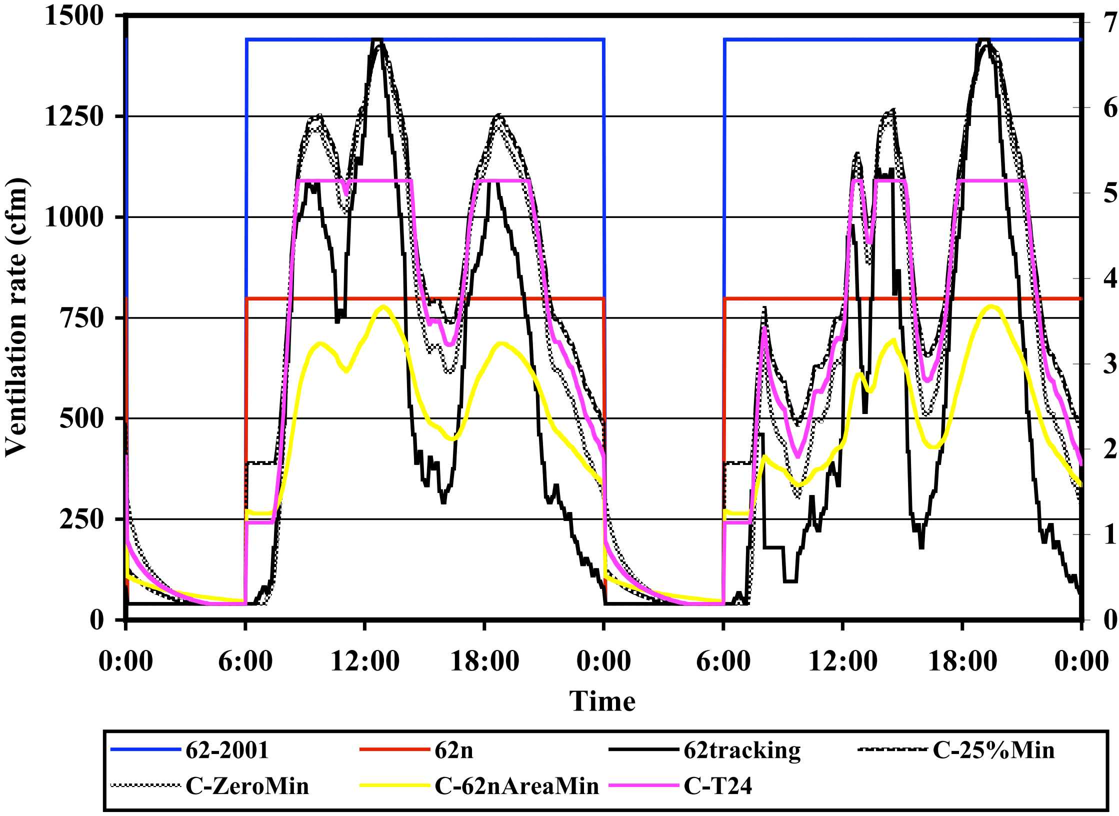


Figure 7 Fast Food Restaurant Ventilation Rates over Friday and Saturday

3.2 Carbon Dioxide Concentration

Table 6 summarizes the indoor CO_2 concentrations for the ventilation strategies and spaces in terms of the average and maximum concentration during occupancy. The first column of the table also presents the steady-state CO_2 concentration for the 62/2001, 62n and Title 24 cases, as well as the 62/Int case when relevant, based on the values in Table 2.

In all spaces, the average and maximum CO_2 concentrations are lower for the 62/2001 cases than for the other cases, except for C-T24 in the Office. This result is expected due to 62/2001 having the highest ventilation rates compared to the 62tracking and the CO_2 control cases. And while 62tracking and the CO_2 control cases have higher average and maximum CO_2 concentrations relative to the 62/2001 case, they are almost always within about 200 mg/m^3 (about 100 parts per million by volume (ppm(v))) of the 62/2001 values. Also, the CO_2 control cases almost always have average and maximum concentrations below the idealized 62tracking case, which indicates good control of occupant-generated contaminants. In all cases the maximum CO_2 concentration during occupancy is less than the steady-state concentration based on the design value in the first column. These differences are generally on the order of 200 mg/m^3 (roughly 100 ppm(v)) except for the Conference Room where the design occupancy is never achieved. The 62/Int case, applicable to only the Conference Room and Lecture Hall, has higher CO_2 concentrations than the other 62-based cases as expected. However, the average concentrations during occupancy are still only about 200 mg/m^3 (roughly 100 ppm(v)) above the 62tracking case.

Figures 8 through 13 present the CO_2 concentrations in each of the spaces over one day (two days in selected cases) for the different ventilation strategies. The CO_2 concentrations in the Office in Figure 3 are fairly similar for the six different ventilation strategies. The 62tracking case is higher during unoccupied periods as the ventilation rate during those periods includes only infiltration, and therefore the post-occupancy CO_2 concentration is elevated relative to the other strategies. This residual concentration builds up during the week, and the biggest differences are seen in this plot for Friday. The two 62n cases, 62n and C-62nAreaMin, have higher concentrations than the other cases during occupancy based on the lower design ventilation rates. The Title 24 DCV case has the lowest CO_2 levels in the Office as expected since it has the highest, and in fact constant, ventilation rates during occupancy. In the other spaces, the 62-2001 case has the lowest CO_2 levels due its having the highest ventilation rates.

There is more variation in CO_2 levels among the ventilation strategies for the Conference Room as seen in Figure 9. The two 62n-based cases, 62n and C-62nAreaMin, have lower per person ventilation rates relative to Standard 62, and therefore the CO_2 concentrations are significantly higher. The 62tracking case again has elevated concentrations during unoccupied periods based on only infiltration occurring during these times. The Lecture Hall in Figure 10 shows the same features as the Conference Room, higher concentrations for the 62n-based cases and elevated concentrations for 62tracking during unoccupied periods. The different ventilation strategies have fairly similar CO_2 concentrations in the two classroom cases (Figures 11 and 12). Finally, the Fast Food Restaurant in Figure 13 also exhibits elevated concentrations for the 62n-based cases and elevated concentrations for 62tracking.

From the concentrations in Table 6 and the figures, one sees that the CO_2 control cases result in CO_2 concentrations that are not very different from those in the cases without CO_2 control. While the CO_2 control cases have higher concentrations, the differences are generally on the order of 200 mg/m^3 (100 ppm(v)).

	Indoor CO_2 concentrations during occupancy			
	Average		**Maximum**	
	mg/m^3	(ppm(v))	mg/m^3	(ppm(v))
Office				
62/2001 (1674 mg/m^3, 930 ppm(v))*	1305	725	1555	864
62tracking	1427	793	1571	873
C-ZeroMin	1413	785	1620	900
C-25%Min	1393	774	1613	896
62n (2061 mg/m^3, 1145 ppm(v))*	1512	840	1854	1030
C-62nAreaMin	1573	874	1908	1060
C-T24 (1546 mg/m^3, 859 ppm(v))*	1231	684	1447	804
Conference Room				
62/2001 (1674 mg/m^3, 930 ppm(v))*	1037	576	1471	817
62tracking	1467	815	1661	923
62/Int (2626 mg/m^3, 1459 ppm(v))*	1291	717	2106	1170
C-ZeroMin	1244	691	1575	875
C-25%Min	1183	657	1561	867
62n (3740 mg/m^3, 2078 ppm(v))*	1553	863	2736	1520
C-62nAreaMin	1962	1090	3240	1800
C-T24 (1991 mg/m^3, 1106 ppm(v))*	1202	668	1694	941
Lecture Hall				
62/2001 (1991 mg/m^3, 1106 ppm(v))*	1436	798	1980	1100
62tracking	1926	1070	1980	1100
62/Int (3262 mg/m^3, 1812 ppm(v))*	2032	1129	3078	1710
C-ZeroMin	1606	892	1980	1100
C-25%Min	1568	871	1980	1100
62n (3123 mg/m^3, 1735 ppm(v))*	1962	1090	2952	1640
C-62nAreaMin	2299	1277	3024	1680
C-T24 (1991 mg/m^3, 1106 ppm(v))*	1469	816	1962	1090
Classroom				
62/2001 (1991 mg/m^3, 1106 ppm(v))*	1559	866	1962	1090
62tracking	1827	1015	1962	1090
C-ZeroMin	1688	938	1980	1100
C-25%Min	1656	920	1980	1100
62n (2113 mg/m^3, 1174 ppm(v))*	1647	915	2088	1160
C-62nAreaMin	1760	978	2124	1180
C-T24 (1991 mg/m^3, 1106 ppm(v))*	1573	874	1944	1080
Portable Classroom				
62/2001 (1532 mg/m^3, 851 ppm(v))*	1262	701	1496	831
62tracking	1418	788	1505	836
C-ZeroMin	1352	751	1519	844
C-25%Min	1332	740	1517	843
62n (1494 mg/m^3, 830 ppm(v))*	1251	695	1480	822
C-62nAreaMin	1310	728	1499	833
C-T24 (1399 mg/m^3, 777 ppm(v))*	1222	679	1384	769
Fast Food Restaurant				
62/2001 (1674 mg/m^3, 930 ppm(v))*	1132	629	1640	911
62tracking	1566	870	1656	920
C-ZeroMin	1314	730	1667	926
C-25%Min	1246	692	1636	909
62n (2461 mg/m^3, 1367 ppm(v))*	1463	813	2322	1290
C-62nAreaMin	1687	937	2412	1340
C-T24 (1991 mg/m^3, 1106 ppm(v))*	1318	732	1908	1060

* Steady-state CO_2 concentration based on the design ventilation rate from Table 2.

Table 6 Summary of Carbon Dioxide Concentrations

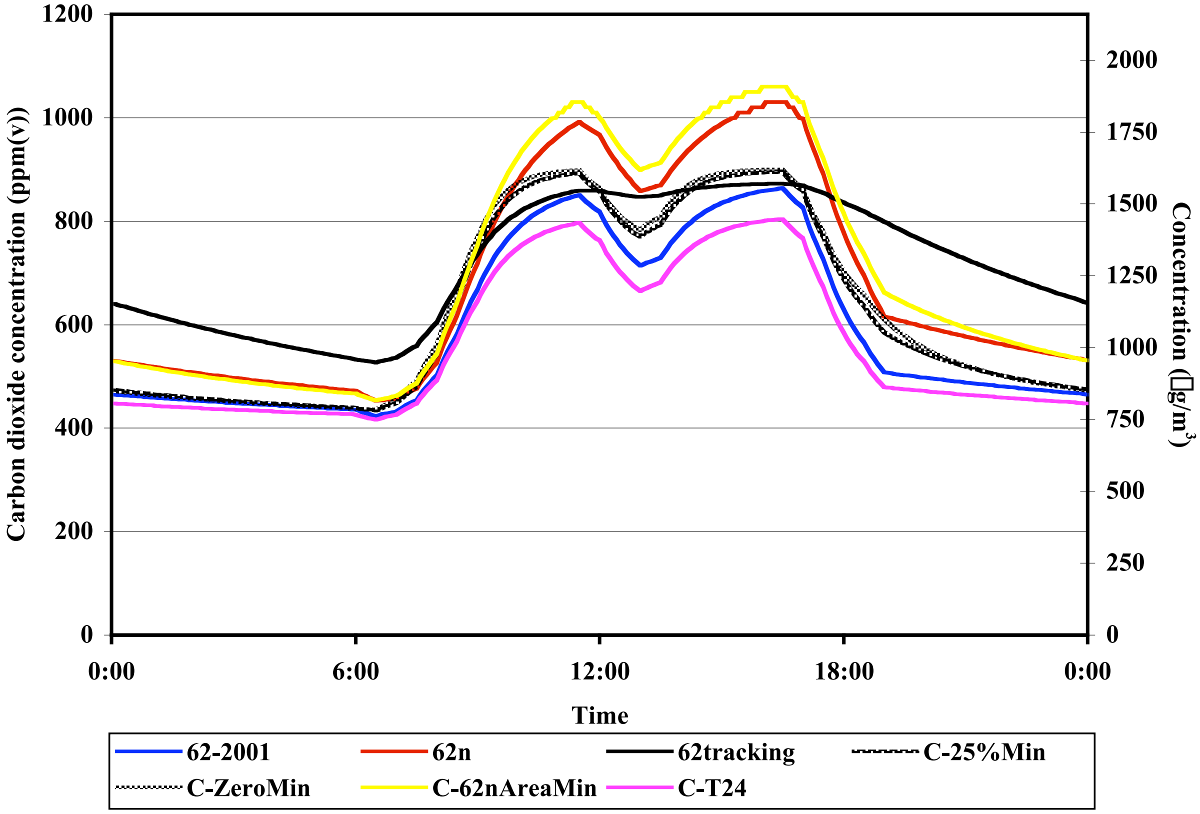


Figure 8 Office CO$_2$ Concentrations during Weekday (Friday)

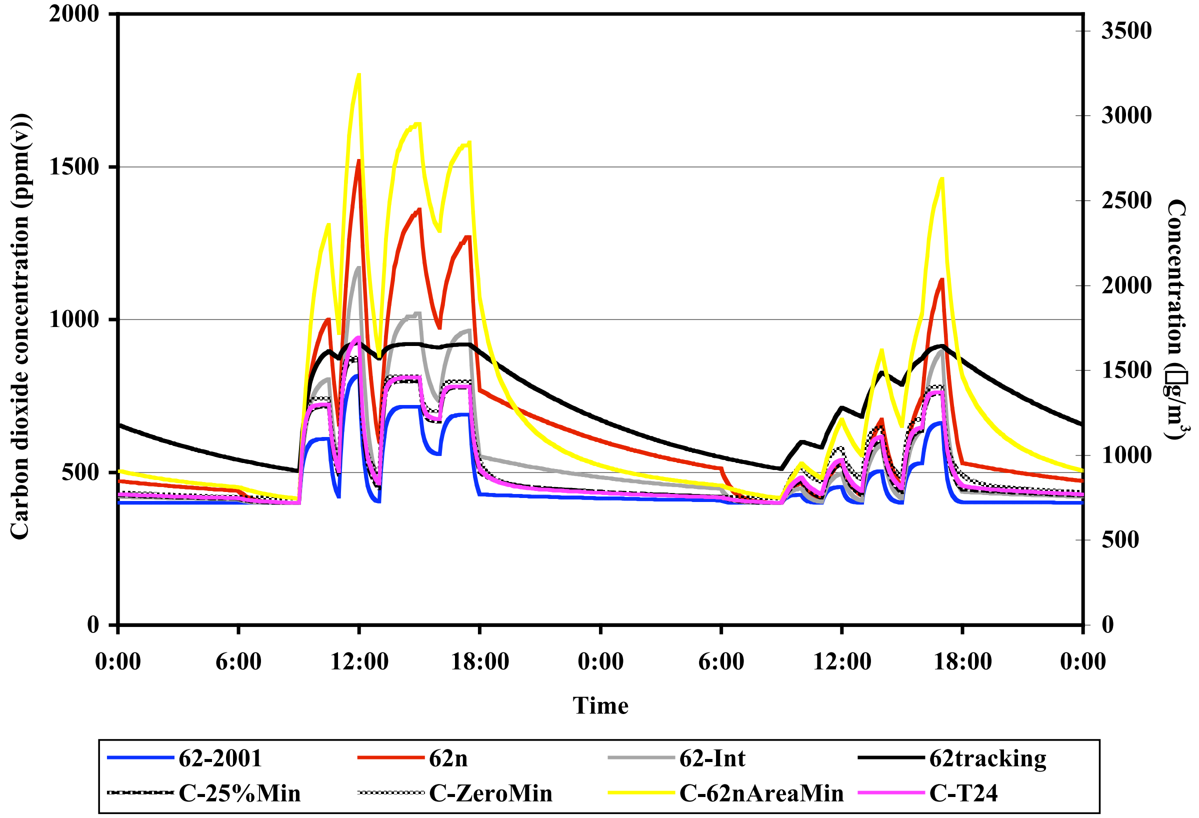


Figure 9 Conference Room CO$_2$ Concentrations during Week (Wednesday and Thursday)

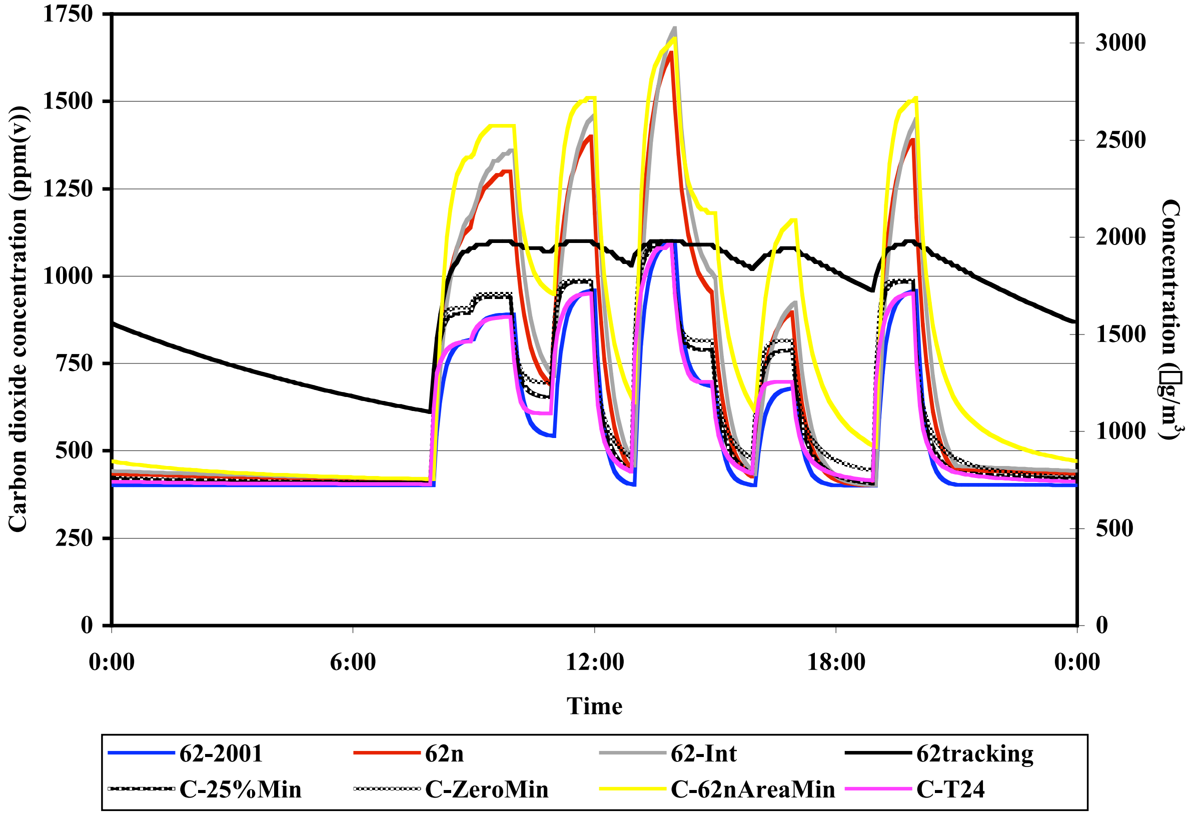


Figure 10 Lecture Hall CO_2 Concentrations during Week (Friday)

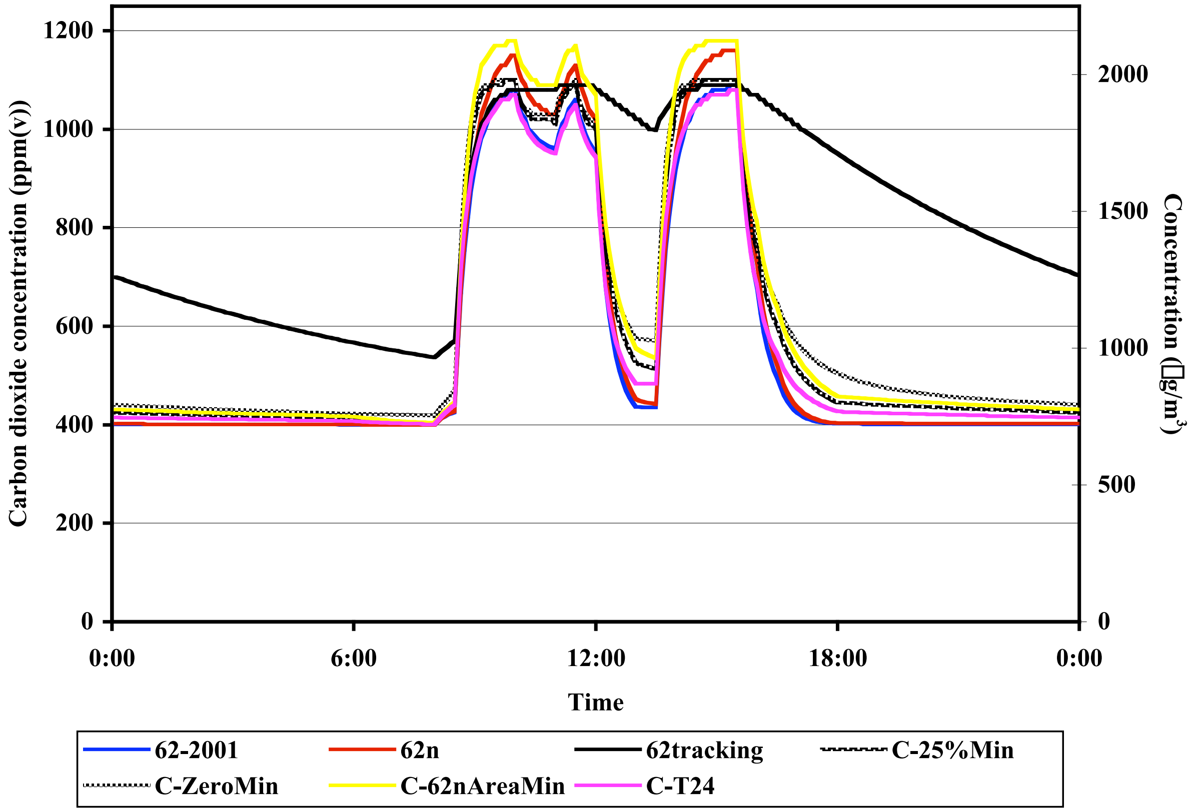


Figure 11 Classroom CO_2 Concentrations during Week (Friday)

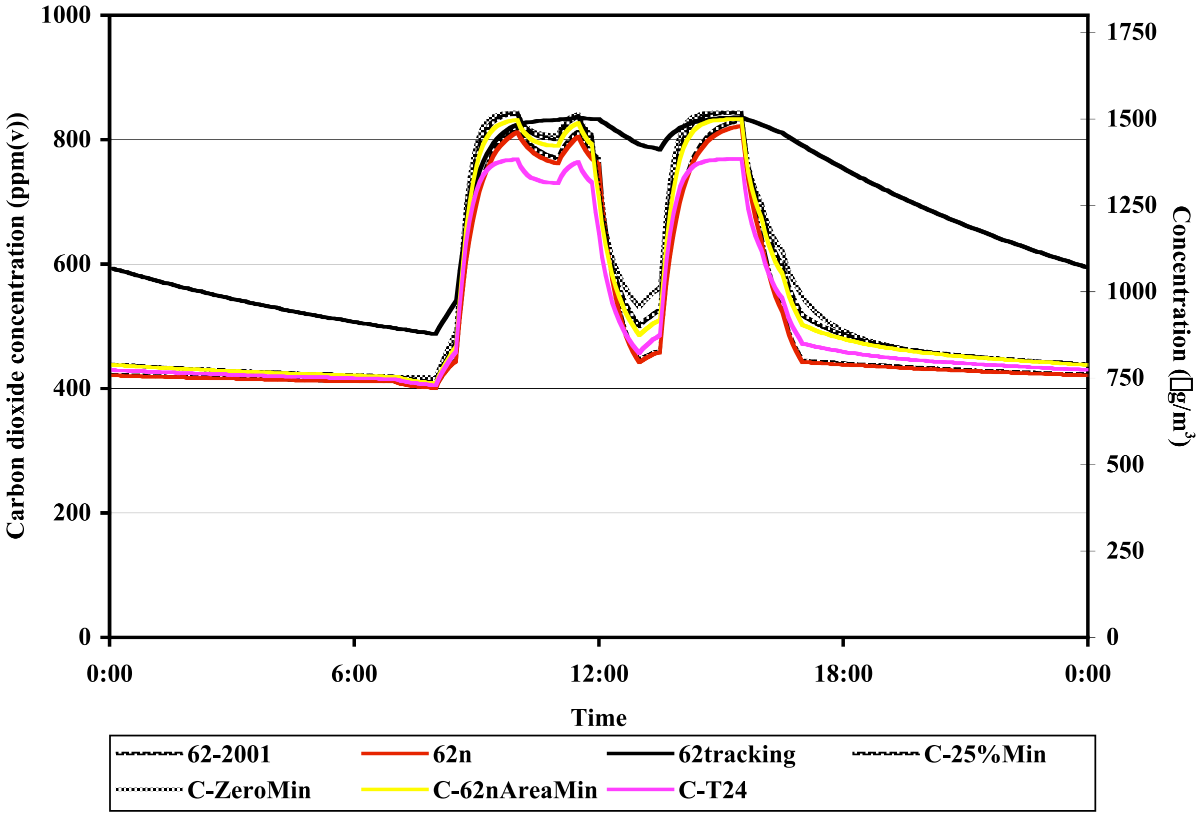


Figure 12 Portable Classroom CO_2 Concentrations during Week (Friday)

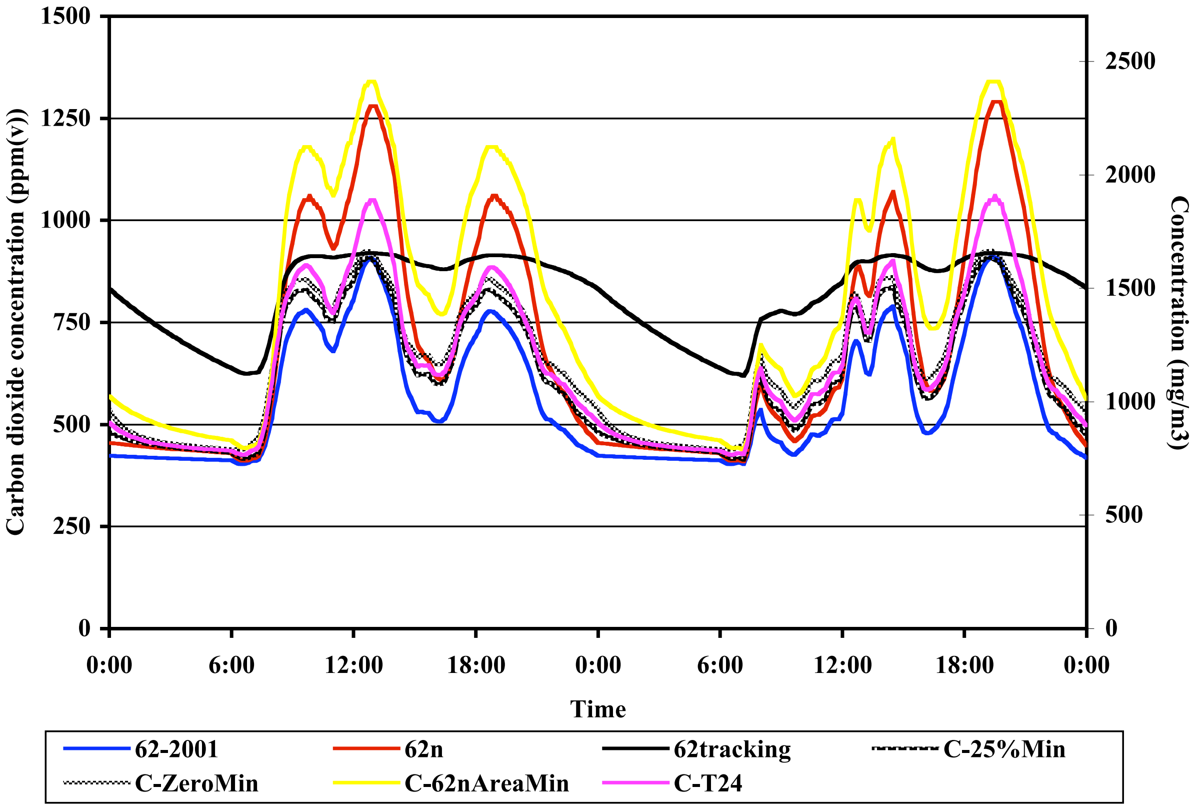


Figure 13 Fast Food Restaurant CO_2 Concentrations over Friday and Saturday

3.3 VOC Concentration

Table 7 summarizes the indoor VOC concentrations for the ventilation strategies in each of the spaces in terms of the average and maximum concentrations during occupancy. The first column of the table also presents the steady-state VOC concentration for the various cases based on the design ventilation rates from Table 2. Figures 14 through 19 present the VOC concentrations in each of the spaces over one day (two in selected cases). Note that the averages in Table 7 are less than 0.4 mg/m^3 in all cases and less than 0.1 mg/m^3 in most cases. While these concentrations are on the low end of those measured in the field, they are dependent on the assumed source strengths during occupied and unoccupied periods and on the assumed infiltration rate during the unoccupied periods. The maximum concentrations are closer to, and in several cases above, 1 mg/m^3 as a result of increases in concentration over unoccupied periods as discussed below.

In all spaces, the average and maximum VOC concentrations are lower for the 62/2001case than for the other cases, except C-T24 in the Office, as expected. And while the 62tracking and CO_2 control cases have higher average concentrations than the 62/2001 case, these averages are generally only two to three times higher and always below 0.4 mg/m^3. Also, the CO_2 control cases almost always have average concentrations that are close to or even below the 62tracking case. If one is willing to assume that 62tracking, which is clearly in compliance with the standard, provides adequate control of building-related contaminants, then the CO_2 DCV cases also control these contaminants on average. The 62n-based CO_2 control case (C-62nAreaMin) also has an average VOC concentration that is generally within a factor of two of the 62n case, again indicating reasonable control of building-related contaminants. The only exception is in the Conference Room where the initial VOC concentration for C-62nAreaMin is elevated at the start of the day. It is worth noting that the average VOC level in non-office spaces with CO_2 control is almost always lower than the VOC level in the Office with the Standard 62-2001 ventilation rate. Therefore, if the VOC level in the Office based on Standard 62 is acceptable, then the level in the other spaces is also acceptable. Of course, this conclusion is based on the same VOC emission rates per unit floor area in all the spaces, which may not always be a good assumption.

The maximum VOC concentrations during occupancy are generally greater than the steady-state VOC concentrations from Table 2 by a factor of two or three, but in some cases by more than an order of magnitude. These maximum concentrations are so much higher due to the increase in VOC concentrations over unoccupied periods when the spaces have an infiltration rate of only 0.1 h^{-1}. Note that the steady-state concentrations are based on the design ventilation rates and are not impacted by the elevated initial concentrations that may exist early in the morning. The maximum concentrations are strongly dependent on the unoccupied infiltration rate and the relative values of the source strength during occupied and unoccupied periods, and therefore the relative values of the different cases are more informative than the absolute values. The highest maximum concentrations are seen for 62tracking or the CO_2 control cases where there is very little ventilation in the early part of occupancy. The maximum concentrations confirm the observation above that if the 62tracking case is considered to control IAQ acceptably then the DCV cases should also be considered acceptable as the maximum concentrations for the DCV cases are near or below the 62tracking cases in all situations.

Figure 14 presents the VOC concentrations in the Office space. The patterns are similar for the different ventilation cases with the exception of the elevated concentrations early in the day for 62tracking and C-ZeroMin, where the VOC source increases as soon as the system comes on but the ventilation rate does not increase until later in the morning. A slight increase in concentration is seen at mid-day for the 62tracking and the CO_2 control cases when the ventilation rate is reduced in response to the lower occupancy. After the system is turned off at 1900, the VOC concentration increases steadily and reaches its maximum value just before the system comes back on the next morning. Figures 15 and 16 shows similar trends for the Conference Room and Lecture Hall, with dramatic increases in concentration at system startup for 62tracking and C-ZeroMin. Once the ventilation rates increase, the concentrations reduce by a factor of 5 to 10. The increases in VOC concentrations during periods of low occupancy are more evident in these spaces than in the Office. The two classrooms show similar results in Figures 17 and 18, as does the Fast Rood Restaurant in Figure 19.

The average and maximum VOC concentrations in Table 7 are both heavily influenced by the elevated concentrations at the start of occupancy. The figures reveal that once the early morning transients die out, the differences between the various ventilation strategies become less significant. Looking at the concentrations in the late afternoon, the ratio of maximum to minimum VOC concentrations for the various cases, neglecting the idealized 62tracking case, is about 1.5 in the Office, at most 3 or 4 in the Conference Room, Lecture Hall and classrooms, and around 2 in the fast food restaurant.

	Indoor VOC concentrations during occupancy (mg/m^3)	
	Average	**Maximum**
Office		
62/2001 (0.21 mg/m^3)*	0.22	0.58
62tracking	0.34	0.89
C-ZeroMin	0.37	0.96
C-25%Min	0.32	0.80
62n (0.03 mg/m^3)*	0.31	0.67
C-62nAreaMin	0.35	0.74
C-T24 (0.18 mg/m^3)*	0.19	0.55
Conference Room		
62/2001 (0.03 mg/m^3)*	0.03	0.03
62tracking	0.30	0.90
62/Int (0.06 mg/m^3)*	0.06	0.06
C-ZeroMin	0.22	1.06
C-25%Min	0.07	0.12
62n (0.09 mg/m^3)*	0.09	0.09
C-62nAreaMin	0.25	0.50
C-T24 (0.04 mg/m^3)*	0.09	0.20
Lecture Hall		
62/2001 (0.01 mg/m^3)*	0.02	0.28
62tracking	0.04	0.32
62/Int (0.03 mg/m^3)*	0.04	0.34
C-ZeroMin	0.03	0.42
C-25%Min	0.03	0.37
62n (0.03 mg/m^3)*	0.03	0.33
C-62nAreaMin	0.06	0.42
C-T24 (0.01 mg/m^3)*	0.03	0.41
Classroom		
62/2001 (0.06 mg/m^3)*	0.06	0.06
62tracking	0.18	0.99
C-ZeroMin	0.19	1.03
C-25%Min	0.10	0.31
62n (0.06 mg/m^3)*	0.06	0.07
C-62nAreaMin	0.11	0.35
C-T24 (0.06 mg/m^3)*	0.08	0.26
Portable Classroom		
62/2001 (0.09 mg/m^3)*	0.09	0.18
62tracking	0.22	1.04
C-ZeroMin	0.24	1.10
C-25%Min	0.17	0.64
62n (0.08 mg/m^3)*	0.09	0.17
C-62nAreaMin	0.15	0.52
C-T24 (0.07 mg/m^3)*	0.12	0.41
Fast Food		
62/2001 (0.03 mg/m^3)*	0.03	0.06
62tracking	0.10	0.36
C-ZeroMin	0.07	0.31
C-25%Min	0.05	0.18
62n (0.05 mg/m^3)*	0.05	0.11
C-62nAreaMin	0.08	0.20
C-T24 (0.04 mg/m^3)*	0.06	0.21

* Steady-state VOC concentration based on the design ventilation rate from Table 2.

Table 7 Summary of VOC Concentrations

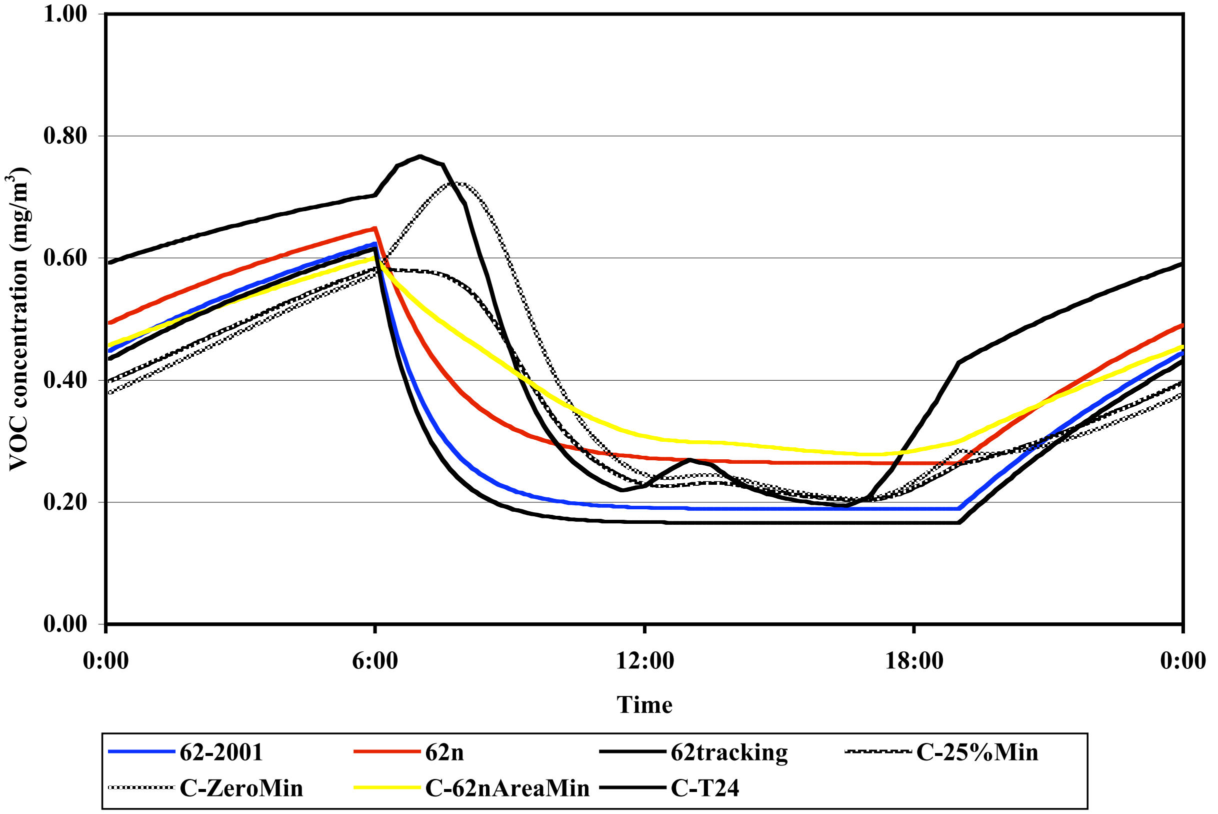


Figure 14 Office VOC Concentrations during Weekday (Friday)

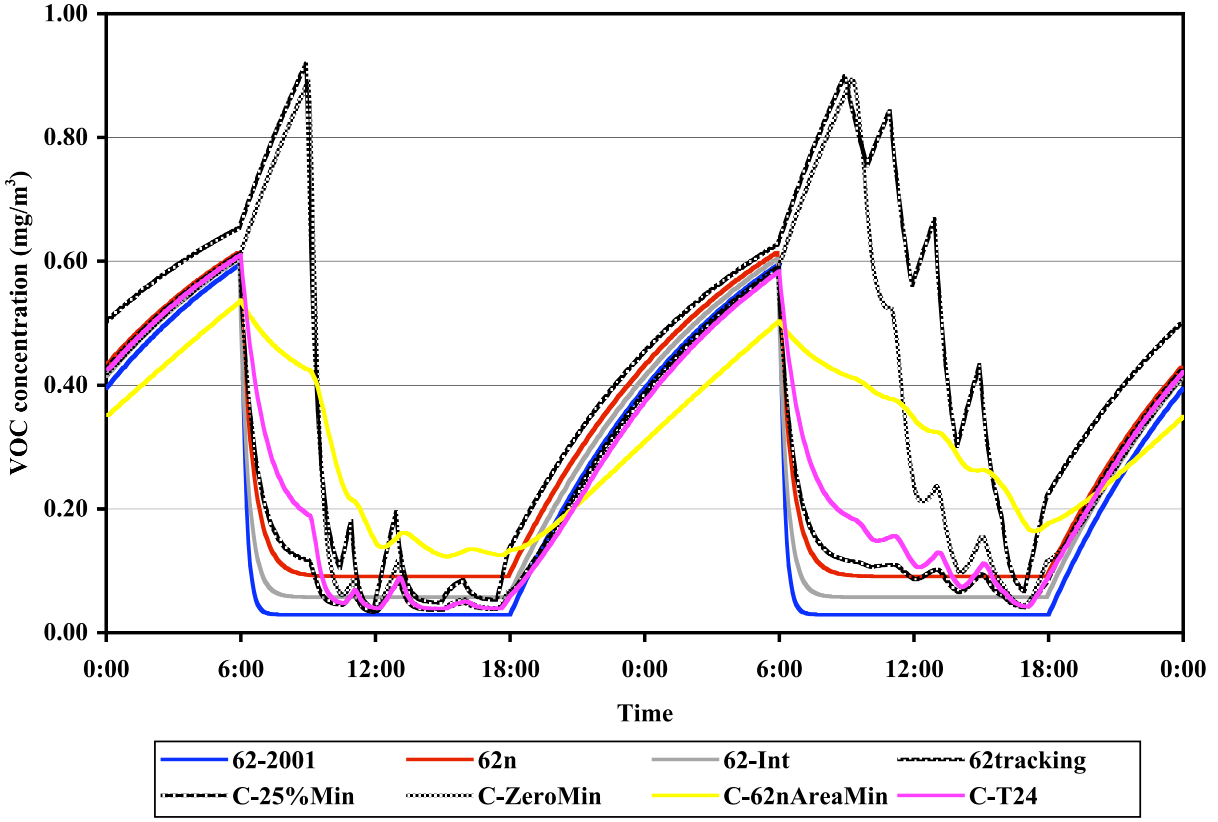


Figure 15 Conference Room VOC Concentrations during Week (Wednesday and Thursday)

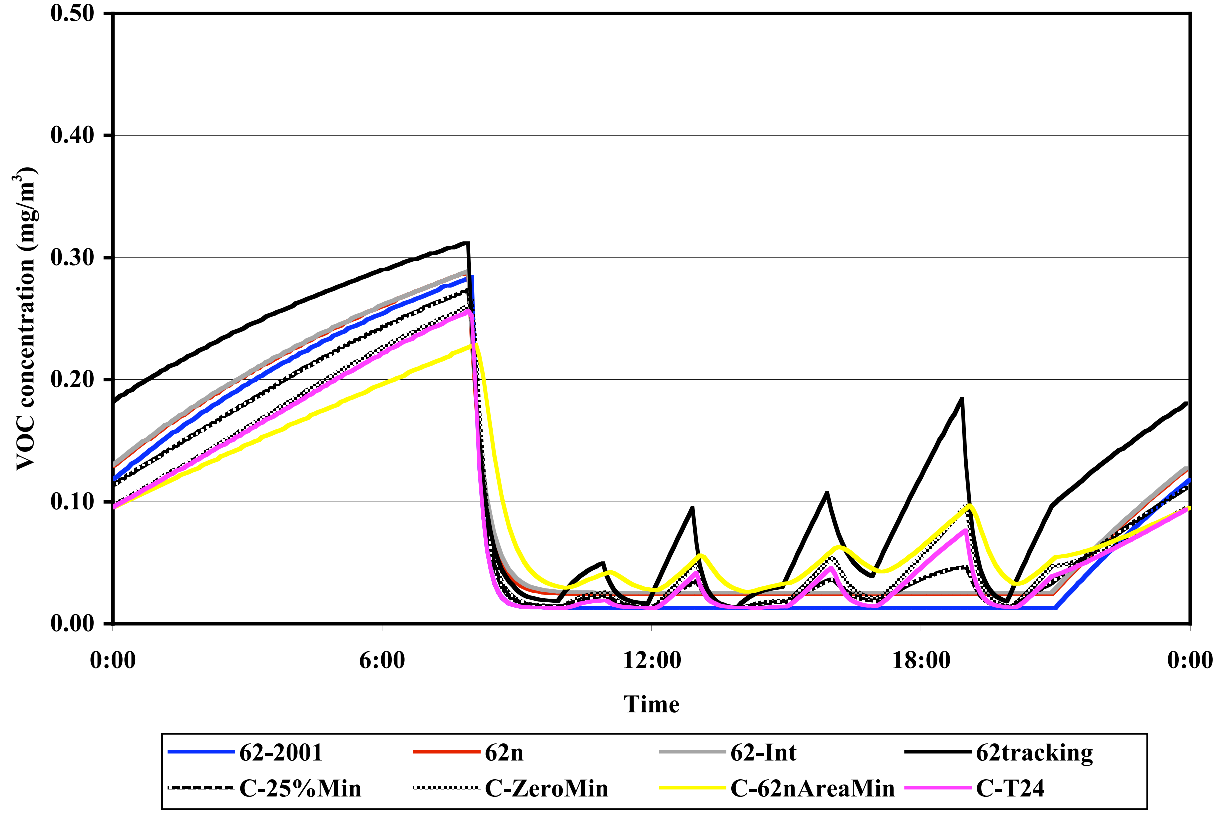


Figure 16 Lecture Hall VOC Concentrations during Week (Friday)

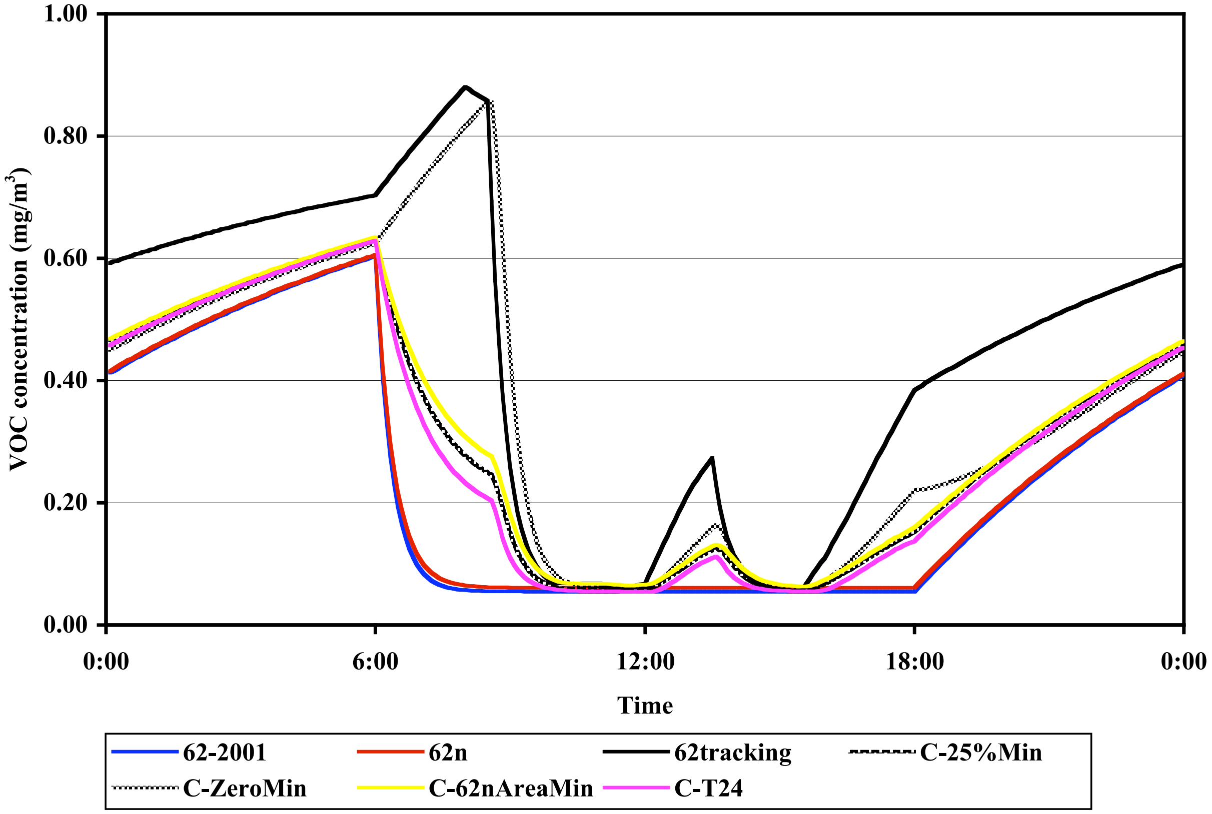


Figure 17 Classroom VOC Concentrations during Week (Friday)

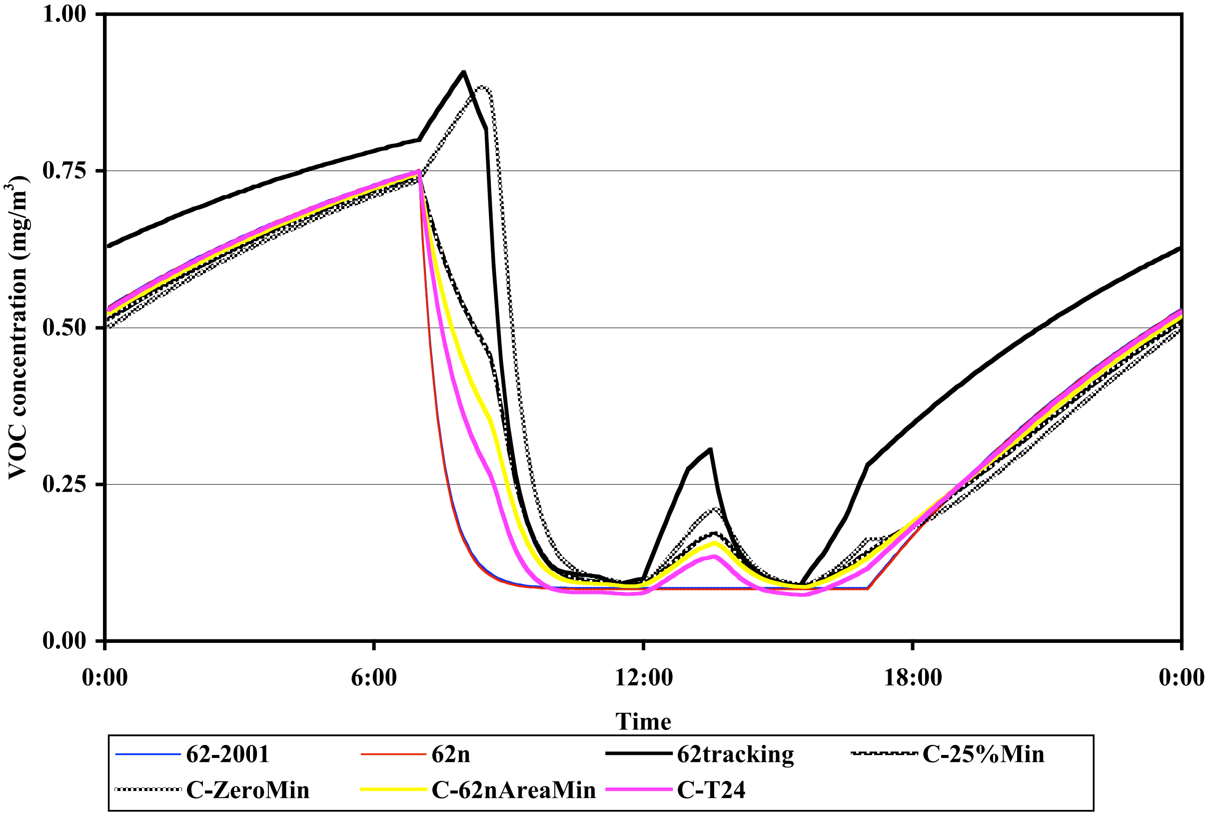


Figure 18 Portable Classroom VOC Concentrations during Week (Friday)

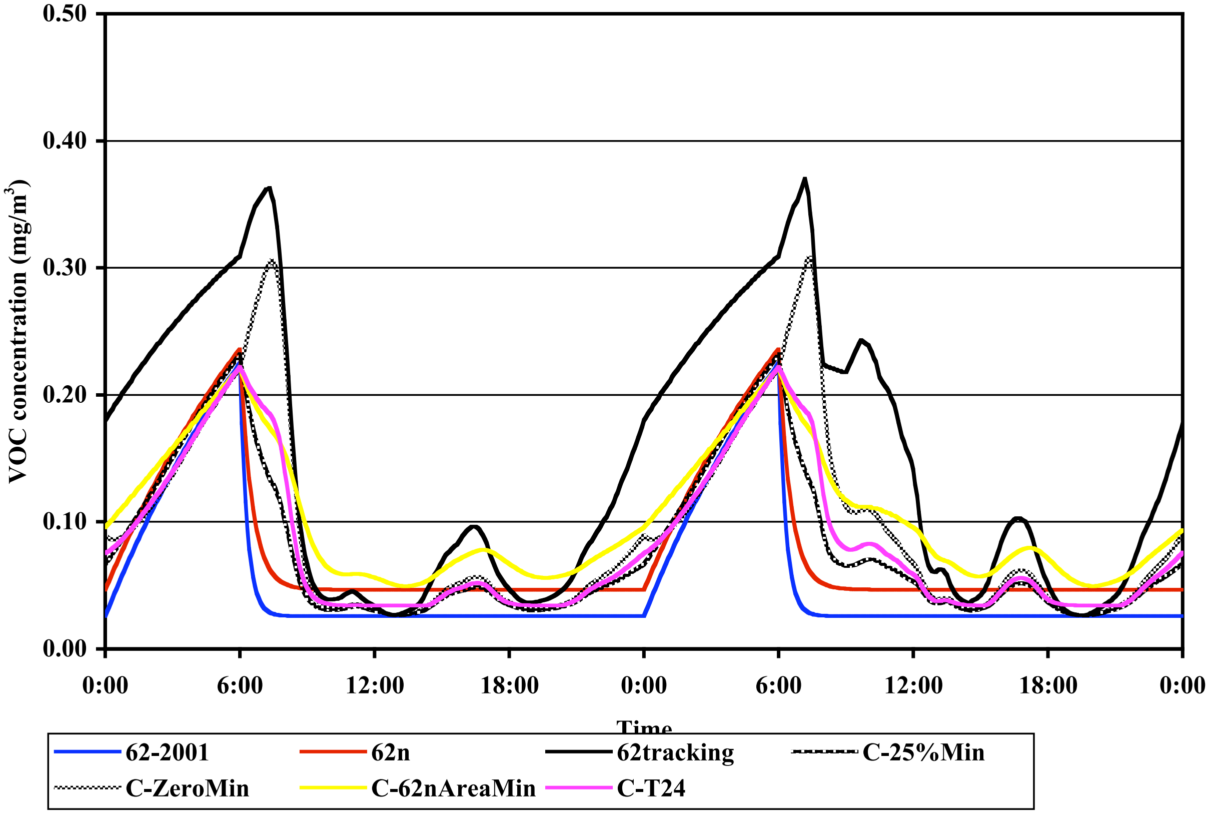


Figure 19 Fast Food Restaurant VOC Concentrations over Friday and Saturday

3.4 Energy Loads

Table 8 summarizes the estimated energy loads associated with ventilation for each of the spaces. For each city, this table presents the annual energy load associated with ventilation for each ventilation strategy in units of MJ/m^2 to account for differences in the sizes of the spaces. Appendix A contains more details on the energy loads, including the heating, sensible cooling and latent cooling for each case. In general, the CO_2 control cases use less energy than the constant ventilation rate cases, and the 62n case uses less than 62/2001 except in the Portable Classroom where the 62n ventilation rate is higher. The magnitude of these reductions in a particular city and space combination is a fairly complex function of climate (relative amounts of heating and cooling), ventilation rate per unit floor area as shown in Table 2 (which also impacts the heating load via the balance point), internal heat loads shown in Table 3 (which also impacts balance point) and occupancy patterns.

In the Office space, 62tracking and the two 62-based CO_2 control cases have energy loads that are roughly 20 % lower than the straight 62-2001 case. (The loads in San Francisco are so low in the Office space that the reductions are not discussed.) Compared to 62/2001, the addendum 62n rates decrease the ventilation-induced energy load by 30 % to 60 % depending on the city, with the largest reduction in the heating-dominated Minneapolis climate. Implementing CO_2 control under 62n leads to further variable reductions in the energy loads among the different cities, ranging from around 10 % to 30 %. For the Office space, the biggest reductions in energy under CO_2 control occur in Minneapolis, which is a heating dominated climate. These reductions are larger under heating due to the combined impact of lower ventilation rates under CO_2 control and decreased balance point temperatures due to these lower rates. Another reason for larger reductions under heating is that the ventilation rates tend to be lower early in the day when the outdoor temperature is lower. The energy load increases in the Office under C-T24, but as noted earlier that is not really a DCV case in the Office and in fact has a higher ventilation rate than required by Standard 62-2001.

The reductions in energy load for the CO_2 control cases, including C-T24, are much larger in the Conference Room and Lecture Hall given the higher design ventilation rates per unit floor area and impact of these rates on balance point temperature. The reduction in energy load from the 62/2001 to 62n cases is also much larger than in the Office, more than 50 % in all cases and as high as 80 %. Implementing CO_2 control under 62n leads to further reductions in energy load. The results for the classrooms are similar in relative magnitude to the changes seen in the other cases, with the exception of the difference between 62n and 62/2001. As noted earlier, the ventilation rate under 62n in the Portable Classroom is actually higher than under 62/2001, leading to a slight increase in the energy load. Otherwise, implementing CO_2 control under Standard 62, Title 24 or 62n results in energy reductions from around 30 % to 50 % depending on the city. Implementing CO_2 control under Standard 62 or Title 24 in the Fast Food Restaurant reduces the energy load by around 40 % to as high as 75 %, again depending on the city. The lower rates under addendum 62n reduce the energy load by around 50 % relative to 62/2001, with an 86 % reduction in Los Angeles due to a greater relative reduction in the heating load compared to the other cities.

The energy reductions for C-62nAreaMin relative to 62/2001 are as high as 80 % to 90 % in many cases based on the lower rates in addendum 62n. Also, the percent reductions in the spaces studies are much greater in the mild climates than the more extreme climates.

	Annual Energy Load due to Ventilation (MJ/m^2)					
	Bakersfield	Los Angeles	Sacramento	San Francisco	Miami	Minneapolis
Office						
62/2001	30	6	18	1	117	63
62tracking	24	5	15	1	85	34
C-ZeroMin	26	5	17	1	87	35
C-25%Min	27	5	17	1	93	37
62n	20	4	12	1	79	18
C-62nAreaMin	19	4	12	1	71	13
C-Title24	35	7	21	1	135	94
Conference Room						
62/2001	357	173	348	298	670	727
62tracking	71	25	66	44	147	148
62/Int	169	63	162	127	332	356
C-ZeroMin	111	41	104	73	228	233
C-25%Min	151	56	145	106	303	320
62n	93	22	89	53	205	213
C-62nAreaMin	30	4	22	4	87	71
C-Title24	129	48	122	85	248	280
Lecture Hall						
62/2001	1049	528	1010	931	1943	2168
62tracking	383	142	362	292	790	841
62/Int	464	127	437	322	962	1041
C-ZeroMin	568	219	537	428	1143	1231
C-25%Min	645	248	614	502	1278	1395
62n	508	157	479	372	1025	1117
C-62nAreaMin	242	40	215	95	620	618
C-Title24	714	302	687	585	140	1521
Classroom						
62/2001	197	56	194	132	406	446
62tracking	81	16	74	34	203	202
C-ZeroMin	97	19	87	43	236	228
C-25%Min	105	21	93	45	271	264
62n	168	43	166	105	364	397
C-62nAreaMin	88	16	80	33	242	230
C-Title24	119	23	108	53	300	303
Portable Classroom						
62/2001	108	36	106	79	219	236
62tracking	62	17	57	35	135	138
C-ZeroMin	64	17	61	37	143	146
C-25%Min	71	17	65	40	157	163
62n	110	38	109	81	222	240
C-62nAreaMin	76	17	72	44	166	175
C-Title24	94	27	92	63	199	212
Fast Food						
62/2001	1021	514	1041	1018	1875	2171
62tracking	362	94	326	229	833	847
C-ZeroMin	516	158	489	381	1109	1204
C-25%Min	574	180	550	442	1228	1357
62n	435	74	421	254	995	1106
C-62nAreaMin	222	29	174	50	679	672
C-Title24	490	125	465	345	1090	1178

Table 8 Summary of Energy Loads

4. DISCUSSION

The objective of this study was to examine the ventilation, indoor air quality and energy impacts of CO_2 demand controlled ventilation in a number of different space types and climates based on the project goal of developing application guidance for potential users of CO_2 DCV. The results indicate that these impacts are dependent on the details of the spaces including occupancy patterns, ventilation rate requirements and ventilation system operating schedule as well as the assumptions used in the analysis, including contaminant source strengths and system-off infiltration rates. The results and conclusions presented in this report are therefore specific to the cases studied; however, some general conclusions can be reasonably made and the methodology can be extended to other cases and even used in the design process as discussed below.

In terms of the ventilation rates, the simulations results yield the expected result that basing design ventilation rates on design occupancy levels results in "overventilation" for potentially many hours depending on the occupancy schedule. While ventilating at the design rate, even under low occupancy, may have indoor air quality benefits in terms of better dilution of indoor contaminant sources, there is an energy penalty. The CO_2 control cases help avoid such periods of overventilation, but generally result in relatively low ventilation rates early in the day when occupancy is low. These low rates result in contaminant buildup, particularly of those contaminants associated with the building, including potential exposure to contaminants that may have built up overnight when the system was off. The extent of such contaminant buildup is highly dependent on the source strengths in the unoccupied building, for which only very limited data is available, and fan off infiltration rates, which are highly building specific and weather dependent. Therefore it is very hard to generalize about early occupancy exposure, other than stating that CO_2 control strategies with a nonzero base ventilation rate, such as C-25%Min, C-62nAreaMin and C-T24, will help to temper such exposure. Pre-occupancy "flush out" strategies (a requirement of Title 24, but not Standard 62-2001) may also be helpful in lessening such exposure, but need to be considered for the given space and climate, as early morning ventilation can have energy implications that depend on temperature and humidity variations over the day.

As expected, the 62n rates are significantly lower than the 62/2001 rates for all but the two classroom spaces. While this reduction has generated some questions based on potential IAQ concerns, the CO_2 and VOC simulations provide some insight into this question.

While CO_2 is not a contaminant of concern at typical indoor levels, it has become viewed as an indicator of occupant-generated contaminants and is useful in this respect if the limitations are understood. In particular, it provides information on the acceptability of the space in terms of odor from human bioeffluents and perhaps the level of other occupant generated contaminants, but is not a comprehensive indicator of overall indoor air quality. Many have come to view an indoor CO_2 concentration of 1800 mg/m^3 (1000 ppm(v)) as a threshold separating good and bad indoor air quality, but in reality 1800 mg/m^3 (1000 ppm(v)) CO_2 has no significance from a health or comfort perspective (ASTM 2002) and is only of interest based on it being the expected steady-state concentration at ventilation rates of about 8 L/s (17 cfm) per person and an outdoor concentration of 540 mg/m^3 (300 ppm(v)). Nonetheless, the average and maximum indoor CO_2 concentrations serve as metrics for comparing the different cases.

As expected, ventilating at the Standard 62-2001 rate whenever the system is operating results in the lowest CO_2 concentrations, except for the offices where Title 24 results in lower concentrations. However, the CO_2 control cases increase the average and maximum CO_2 concentrations during occupancy by only about 180 mg/m^3 (100 ppm(v)). In terms of the impact on bioeffluent perception, 180 mg/m^3 (100 ppm(v)) is not very significant. Specifically, based on the relationship between percent of occupants dissatisfied with human bioeffluents and CO_2 concentration (ECA 1992), a change of 180 mg/m^3 (100 ppm(v)) corresponds to an increase in the percent dissatisfied of only about 2 %.

The use of ventilation rates based on addendum 62n resulted in more significant increases in indoor CO_2 levels. The average concentrations increased from 180 mg/m^3 (100 ppm(v)) or less to about 540 mg/m^3 (300 ppm(v)) in the Conference Room. The increases in the maximum concentration were larger, up to 900 mg/m^3 (500 ppm(v)) in the Lecture Hall and 1260 mg/m^3 (700 ppm(v)) in the Conference Room. These increases in the maximum concentrations are more significant but still below any level of concern based on health (ASTM 2002). None of the maximum concentrations exceeded 3060 mg/m^3 (1700 ppm(v)), which corresponds to about 35 % dissatisfaction with odor from human bioeffluents on the part of unadapted visitors to a space and about 12 % dissatisfaction on the part of adapted occupants (ECA 1992). The term adapted refers to the fact that people become accustomed to body odors relatively quickly, in less than a minute, and therefore express lower levels of dissatisfaction at the same level of body odor (or CO_2) than individuals who have not yet become adapted to these odors.

For some of the CO_2 control scenarios, the indoor CO_2 level built-up during the week, but this was due to the value assumed for infiltration when the system was off. Note that while there is not a great deal of data on commercial building infiltration rates, the value used in these simulations is likely conservatively low for most building-climate combinations. In fact, a low value was selected intentionally to highlight the impact of contaminant build-up during unoccupied periods. The magnitude of the build-up depended on the details of the control algorithm, but was rarely more than about 180 mg/m^3 (100 ppm(v)).

Indoor VOC concentrations were calculated to assess the impact of CO_2 control on non-occupant generated contaminants, for example those emitted by building materials and furnishings. Based on the assumed emission rates, which were not particularly low relative to the limited data from field studies, the average indoor VOC levels during occupancy were always less than 0.4 mg/m^3 and less than 0.1 mg/m^3 in most cases. While the lack of definitiveness of the VOC emission rate values limits the reliability of the predicted VOC levels in absolute terms, the relative comparison between cases is far more reliable. Using the 62tracking case, which complies with Standard 62-2001, as a baseline, all the other cases have average VOC concentrations that are close to or below this idealized case. If one is willing to accept that 62tracking provides adequate control of building-related contaminants, then the CO_2 DCV cases also control these contaminants on average. The CO_2 control cases had higher VOC concentrations than the reference cases based on Standard 62-2001 and addendum 62n, with the greatest increase in the Conference Room based on its low occupancy early in the day. The average concentrations, and more so the maximum concentrations, were heavily influenced by the build-up in concentration during unoccupied hours, which in turn depend on the values, assumed for the fan-off infiltration rate and VOC emission rate. As discussed earlier, these elevated concentrations early in the day can be tempered by a nonzero minimum ventilation rate under CO_2 control (as with C-25%Min, C-62nAreaMin and C-Title24) or with an early morning flush-out. That latter strategy was not evaluated as part of this project, but this simulation approach could be used to investigate its potential benefits. Note that while the VOC results are dependent on the assumed emission rates, they can be scaled up or down linearly for other emission rates as long as the two-to-one ratio of occupied to unoccupied emission rate is maintained.

The annual energy load reductions due to the use of CO_2 control were significant in most of the cases, ranging from 10 % to 80 % depending on the space type, climate and ventilation strategy. For the Office , the reductions are generally around 20 %, given the relatively stable occupancy pattern in that space relative to some of the others. Spaces with more variability in occupancy, such as the Conference Room and Lecture Hall, exhibit larger energy reductions. The energy load reductions associated with the use of addendum 62n relative to the ventilation requirements in Standard 62-2001 are as large as 30 % to 50 % in the spaces where the 62n rates are lower. However, in the two classroom spaces, the 62n rates are similar to those based on Standard 62-2001 and therefore no significant difference is seen. The most significant reductions are seen for the 62n DCV case relative to the Standard 62 baseline case.

Taking a closer look at the California climates, these results indicate that CO_2 DCV is not likely to provide much energy benefit in offices in the milder climates (Los Angeles and San Francisco) for the relatively stable occupancy patterns used in this study. However in the more "severe" climates of Bakersfield and Sacramento, the savings in the Office were more significant. The spaces with more variable occupancy (Conference Room, Lecture Hall and Fast Food Restaurant) resulted in significant energy savings in all the climates studied. The energy savings in the classroom spaces are strongly dependent on the system operating schedule versus the occupancy schedule, and while significant load reductions were seen in this study, application of CO_2 DCV in classrooms may require more careful consideration.

This study has employed an approach to assessing ventilation, IAQ and energy impacts of different ventilation strategies using the control simulation capabilities of the CONTAMW program. As noted above, this methodology can be applied to other spaces, climates and ventilation strategies to investigate a number of other issues of interest. In particular, the impacts of different VOC source strengths in different spaces and variable emissions patterns over the day would be of interest. Also, the impacts of occupancy levels both lower and greater than those assumed in the design, which does occur in practice, would be worth considering.

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6. REFERENCES

Anderson, K, JV Bakke, O Bjørseth, C-G Bornehag, G Clausen, JK Hongslo, M Kjellman, S Kjærgaard, F Levy, L Mølhave, S Skerfving and J Sundell. 1997. TVOC and Health in Non-Industrial Indoor Environments. Report from a Nordic Scientific Consensus Meeting at Långholmen in Stockholm, 1996. Indoor Air, Vol 7:78-91.

ANSI/ASHRAE/IESNA. 1999. ANSI/ASHRAE/IESNA Standard 90.1-1999: Energy Standard for Buildings Except Low-Rise Residential Buildings. American Society of Heating, Refrigerating, and Air Conditioning Engineers and Illuminating Engineering Society of North America.

ASHRAE. 1997. WYEC2: Weather Year for Energy Calculations 2. American Society of Heating, Refrigerating and Air-Conditioning Engineers.

ASHRAE. 2001a. ANSI/ASHRAE Standard 62-2001, Ventilation for Acceptable Indoor Air Quality. American Society of Heating, Refrigerating and Air-Conditioning Engineers.

ASHRAE 2001b. ASHRAE Handbook of Fundamentals. American Society of Heating, Refrigerating, and Air Conditioning Engineers.

ASTM. 2002. D6245-98 (2002) Standard Guide for Using Indoor Carbon Dioxide Concentrations to Evaluate Indoor Air Quality and Ventilation. American Society for Testing and Materials.

Brandemuehl, MJ and JE Braun. 1999. The Impact of Demand-Controlled and Economizer Ventilation Strategies on Energy Use in Buildings. ASHRAE Transactions 105 (2): 39-50.

Brown, S, MR Sim, MJ Abramson and CN Gray. 1994. Concentrations of Volatile Organic Compounds in Indoor Air - A Review, p. 123-134. Indoor Air, Vol. 4.

Carpenter, SC. 1996. Energy and IAQ Impacts of CO2-Based Demand Controlled Ventilation. ASHRAE Transactions, Vol. 102 (2): 1183-1197.

CEC. 2001. Energy Efficiency Standards for Residential and Nonresidential Buildings. California Energy Commission, P400-01-024.

Daisey, JM, AT Hodgson, WJ Fisk, MJ Mendell, and J Ten Brinks. 1994. Volatile Organic Compounds in Twelve California Office Buildings: Classes, Concentrations, and Sources, p. 3557-3562. In Atmospheric Environment. Vol. 28, No. 22.

Dols, WS and GN Walton. 2002. CONTAMW 2.0 User Manual. National Institute of Standards and Technology, NISTIR 6921.

ECA (European Collaborative Action). 1992. Guidelines for Ventilation Requirements in Buildings, Report No. 11, EUR1449EN. Luxembourg Office for Official Publications of the European Communities.

Emmerich, SJ, JW Mitchell and WA Beckman. 1994. Demand-Controlled Ventilation in a Multi-Zone Office Building. Indoor Environment, Vol. 3: 331-340.

Emmerich, SJ and AK Persily. 2001. State-of-the-Art Review of CO_2 Demand Controlled Ventilation Technology and Application. National Institute of Standards and Technology, NISTIR 6729.

Enermodal. 1995. An Evaluation of the Effect of CO2-Based Demand-Controlled Ventilation Strategies on Energy Use and Occupant-Source Contaminant Concentrations. ASHRAE Research Project 740-TRP. Enermodal Engineering Limited.

EPA. 1999. Exposure Factors Handbook. U.S. Environmental Protection Agency, EPA/600/C-99/001.

Hadwen, GE, JF McCarthy, SE Womble, JR Girman and HS Brightman. 1997. Volatile Organic Compound Concentrations in 41 Office Buildings in the Continental United States. In Proceedings of Healthy Buildings/IAQ'97. Volume 2: 465-470.

Knapp, CL, TL Stoffel and SD Whitaker. 1980. Insolation Data Manual. Solar Energy Research Institute, SERISP-755-789.

Levin, H. 1995. Emissions Testing Data and Indoor Air Quality. Second International Conference on Indoor Air Quality, Ventilation and Energy Conservation in Buildings, 1: 465-482.

Marion W and K Urban. 1995. User's Manual for TMY2s, Typical Meteorological Years, Derived from the 1961-1990 National Solar Radiation Data Base. National Renewable Energy Laboratory, NREL/SP-463-7668, E95004064.

Persily, AK. 2001. Addendum 62n: Revising the Ventilation Rate Procedure. ASHRAE Journal 43 (9): 12-13.

Schell, MB, SC Turner and RO Shim. 1998. Application of CO_2-Based Demand-Controlled Ventilation Using ASHRAE Standard 62: Optimizing Energy Use and Ventilation. ASHRAE Transactions 104 (2): 1213-1225.

Schell, MB and D Int-Hout. 2001. Demand Control Ventilation Using CO_2. ASHRAE Journal 43 (2): 18-29.

Sowa J. 2002. CO_2-Based Occupancy Detection for On-Line Demand Controlled Ventilation Systems. Proceedings of Indoor Air 2002, Vol. 3: 334-339.

Wolkoff, P. 1995. Volatile Organic Compounds – Sources, Measurements, Emissions, and The Impact on Indoor Air Quality. Indoor Air. Supplement No. 3/95.

Appendix A: Details of Energy Simulation Results

This appendix presents the energy simulation results for the six space types for each ventilation control strategy in each city. The tables that follow break down the total energy presented in the body of the report into heating energy and sensible and latent cooling. A separate table is included for each of the six cities.

	Heating (MJ)	Sensible cooling (MJ)	Latent cooling (MJ)	Total cooling (MJ)	Total heating & cooling (MJ)	Total heating & cooling (MJ/m^2)
Office						
62/2001	0	29,800	200	30,000	30,000	30
62tracking	0	23,600	100	23,700	23,700	24
C-ZeroMin	0	25,600	100	25,700	25,700	26
C-25%Min	0	26,300	200	26,500	26,500	27
62n	0	20,200	100	20,300	20,300	20
C-62nAreaMin	0	19,000	100	19,100	19,100	19
C-Title24	0	34,400	200	34,600	34,600	35
Conference Room						
62/2001	17,200	18,400	100	18,500	35,700	357
62tracking	2,400	4,700	0	4,700	7,100	71
62/Int	7,600	9,200	100	9,300	16,900	169
C-ZeroMin	3,900	7,200	0	7,200	11,100	111
C-25%Min	6,000	9,000	100	9,100	15,100	151
62n	3,600	5,700	0	5,700	9,300	93
C-62nAreaMin	300	2,700	0	2,700	3,000	30
C-Title24	4,700	8,200	0	8,200	12,900	129
Lecture Hall						
62/2001	51,800	52,800	300	53,100	104,900	1049
62tracking	18,200	20,000	100	20,100	38,300	383
62/Int	19,800	26,400	200	26,600	46,400	464
C-ZeroMin	26,500	30,100	200	30,300	56,800	568
C-25%Min	30,300	34,000	200	34,200	64,500	645
62n	22,400	28,200	200	28,400	50,800	508
C-62nAreaMin	7,300	16,800	100	16,900	24,200	242
C-Title24	34,400	36,800	200	37,000	71,400	714
Classroom						
62/2001	9,600	10,000	100	10,100	19,700	197
62tracking	2,600	5,400	0	5,500	8,100	81
C-ZeroMin	3,100	6,600	0	6,600	9,700	97
C-25%Min	3,200	7,300	0	7,300	10,500	105
62n	7,800	8,900	100	9,000	16,800	168
C-62nAreaMin	2,300	6,500	0	6,500	8,800	88
C-Title24	3,900	8,000	0	8,000	11,900	119
Portable Classroom						
62/2001	4,700	4,900	0	4,900	9,600	108
62tracking	2,300	3,200	0	3,200	5,500	62
C-ZeroMin	2,200	3,500	0	3,500	5,700	64
C-25%Min	2,500	3,800	0	3,800	6,300	71
62n	4,800	5,000	0	5,000	9,800	110
C-62nAreaMin	2,800	4,000	0	4,000	6,800	76
C-Title24	3,700	4,700	0	4,700	8,400	94
Fast Food						
62/2001	74,200	53,000	400	53,400	127,600	1021
62tracking	18,600	26,400	200	26,600	45,200	362
C-ZeroMin	29,400	34,900	200	35,100	64,500	516
C-25%Min	34,000	37,500	300	37,800	71,800	574
62n	25,600	28,600	200	28,800	54,400	435
C-62nAreaMin	6,600	20,900	200	21,100	27,700	222
C-Title24	27,500	33,500	200	33,700	61,200	490

Table A1 Detailed Energy Loads for Bakersfield

	Heating (MJ)	**Sensible cooling (MJ)**	**Latent cooling (MJ)**	**Total cooling (MJ)**	**Total heating & cooling (MJ)**	**Total heating & cooling (MJ/m^2)**
Office						
62/2001	0	2,700	3,100	5,800	5,800	6
62tracking	0	2,300	2,400	4,700	4,700	5
C-ZeroMin	0	2,300	2,300	4,600	4,600	5
C-25%Min	0	2,400	2,500	4,900	4,900	5
62n	0	1,800	2,100	3,900	3,900	4
C-62nAreaMin	0	1,700	1,900	3,600	3,600	4
C-Title24	0	3,100	3,600	6,700	6,700	7
Conference Room						
62/2001	13,600	1,900	1,800	3,700	17,300	173
62tracking	1,700	400	400	800	2,500	25
62/Int	4,500	900	900	1,800	6,300	63
C-ZeroMin	2,900	600	600	1,200	4,100	41
C-25%Min	3,900	900	800	1,700	5,600	56
62n	1,000	600	600	1,200	2,200	22
C-62nAreaMin	0	200	200	400	400	4
C-Title24	3,300	800	700	1,500	4,800	48
Lecture Hall						
62/2001	43,900	4,200	4,700	8,900	52,800	528
62tracking	10,200	2,000	2,000	4,000	14,200	142
62/Int	8,200	2,100	2,400	4,500	12,700	127
C-ZeroMin	16,100	2,800	3,000	5,800	21,900	219
C-25%Min	18,400	3,100	3,300	6,400	24,800	248
62n	10,900	2,300	2,500	4,800	15,700	157
C-62nAreaMin	900	1,500	1,600	3,100	4,000	40
C-Title24	23,200	3,400	3,600	7,000	30,200	302
Classroom						
62/2001	3,500	1000	1,100	2,100	5,600	56
62tracking	400	600	600	1,200	1,600	16
C-ZeroMin	500	700	700	1,400	1,900	19
C-25%Min	600	700	800	1,500	2,100	21
62n	2,400	900	1000	1,900	4,300	43
C-62nAreaMin	200	700	700	1,400	1,600	16
C-Title24	700	800	800	1,600	2,300	23
Portable Classroom						
62/2001	2,100	500	600	1,100	3,200	36
62tracking	700	400	400	800	1,500	17
C-ZeroMin	700	400	400	800	1,500	17
C-25%Min	700	400	400	800	1,500	17
62n	2,200	600	600	1,200	3,400	38
C-62nAreaMin	700	400	400	800	1,500	17
C-Title24	1,400	500	500	1,000	2,400	27
Fast Food						
62/2001	55,100	4,100	5,100	9,200	64,300	514
62tracking	7,200	2,200	2,400	4,600	11,800	94
C-ZeroMin	13,900	2,800	3,100	5,900	19,800	158
C-25%Min	16,100	3,000	3,400	6,400	22,500	180
62n	4,200	2,200	2,800	5,000	9,200	74
C-62nAreaMin	100	1,600	1,900	3,500	3,600	29
C-Title24	10,000	2,600	3,000	5,600	15,600	125

Table A2 Detailed Energy Loads for Los Angeles

	Heating (MJ)	**Sensible cooling (MJ)**	**Latent cooling (MJ)**	**Total cooling (MJ)**	**Total heating & cooling (MJ)**	**Total heating & cooling (MJ/m^2)**
Office						
62/2001	0	18,100	100	18,200	18,200	18
62tracking	0	14,900	100	15,000	15,000	15
C-ZeroMin	0	16,400	100	16,500	16,500	17
C-25%Min	0	16,600	100	16,700	16,700	17
62n	0	12,200	100	12,300	12,300	12
C-62nAreaMin	0	11,700	100	11,800	11,800	12
C-Title24	0	20,800	100	20,900	20,900	21
Conference Room						
62/2001	22,900	11,800	100	11,900	34,800	348
62tracking	3,600	3,000	0	3,000	6,600	66
62/Int	10,300	5,900	0	5,900	16,200	162
C-ZeroMin	5,700	4,700	0	4,700	10,400	104
C-25%Min	8,700	5,800	0	5,800	14,500	145
62n	5,200	3,700	0	3,700	8,900	89
C-62nAreaMin	500	1,700	0	1,700	2,200	22
C-Title24	6,900	5,300	0	5,300	12,200	122
Lecture Hall						
62/2001	70,000	30,800	200	31,000	101,000	1010
62tracking	24,600	11,500	100	11,600	36,200	362
62/Int	28,200	15,400	100	15,500	43,700	437
C-ZeroMin	35,900	17,700	100	17,800	53,700	537
C-25%Min	41,300	20,000	100	20,100	61,400	614
62n	31,400	16,400	100	16,500	47,900	479
C-62nAreaMin	11,400	10,000	100	10,100	21,500	215
C-Title24	46,800	21,800	100	21,900	68,700	687
Classroom						
62/2001	13,200	6,200	0	6,200	19,400	194
62tracking	3,900	3,500	0	3,500	7,400	74
C-ZeroMin	4,400	4,300	0	4,300	8,700	87
C-25%Min	4,700	4,600	0	4,600	9,300	93
62n	11,100	5,500	0	5,500	16,600	166
C-62nAreaMin	3,800	4,200	0	4,200	8,000	80
C-Title24	5,700	5,100	0	5,100	10,800	108
Portable Classroom						
62/2001	6,300	3,100	0	3,100	9,400	106
62tracking	3,100	2,000	0	2,000	5,100	57
C-ZeroMin	3,100	2,300	0	2,300	5,400	61
C-25%Min	3,400	2,400	0	2,400	5,800	65
62n	6,500	3,100	0	3,200	9,700	109
C-62nAreaMin	3,900	2,500	0	2,500	6,400	72
C-Title24	5,200	3,000	0	3,000	8,200	92
Fast Food						
62/2001	102,500	27,500	100	27,600	130,100	1041
62tracking	26,500	14,100	100	14,200	40,700	326
C-ZeroMin	42,400	18,600	100	18,700	61,100	489
C-25%Min	48,700	19,900	100	20,000	68,700	550
62n	37,700	14,800	100	14,900	52,600	421
C-62nAreaMin	10,600	11,100	100	11,200	21,800	174
C-Title24	40,200	17,800	100	17,900	58,100	465

Table A3 Detailed Energy Loads for Sacramento

	Heating (MJ)	Sensible cooling (MJ)	Latent cooling (MJ)	Total cooling (MJ)	Total heating & cooling (MJ)	Total heating & cooling (MJ/m^2)
Office						
62/2001	0	1,200	0	1,200	1,200	1
62tracking	0	1,000	0	1,000	1,000	1
C-ZeroMin	0	1,100	0	1,100	1,100	1
C-25%Min	0	1,100	0	1,100	1,100	1
62n	0	800	0	800	800	1
C-62nAreaMin	0	800	0	800	800	1
C-Title24	0	1,400	0	1,400	1,400	1
Conference Room						
62/2001	29,000	800	0	800	29,800	298
62tracking	4,200	200	0	200	4,400	44
62/Int	12,300	400	0	400	12,700	127
C-ZeroMin	7,000	300	0	300	7,300	73
C-25%Min	10,200	400	0	400	10,600	106
62n	5,000	300	0	300	5,300	53
C-62nAreaMin	300	100	0	100	400	4
C-Title24	8,200	300	0	300	8,500	85
Lecture Hall						
62/2001	91,200	1,900	0	1,900	93,100	931
62tracking	28,300	900	0	900	29,200	292
62/Int	31,200	1,000	0	1,000	32,200	322
C-ZeroMin	41,600	1,200	0	1,200	42,800	428
C-25%Min	48,800	1,400	0	1,400	50,200	502
62n	36,200	1,000	0	1,000	37,200	372
C-62nAreaMin	8,800	700	0	700	9,500	95
C-Title24	57,000	1,500	0	1,500	58,500	585
Classroom						
62/2001	12,800	400	0	400	13,200	132
62tracking	3,200	200	0	200	3,400	34
C-ZeroMin	4,100	300	0	300	4,400	44
C-25%Min	4,200	300	0	300	4,500	45
62n	10,100	400	0	400	10,500	105
C-62nAreaMin	3,000	300	0	300	3,300	33
C-Title24	4,900	400	0	400	5,300	53
Portable Classroom						
62/2001	6,800	200	0	200	7,000	79
62tracking	3,000	100	0	100	3,100	35
C-ZeroMin	3,100	200	0	200	3,300	37
C-25%Min	3,400	200	0	200	3,600	40
62n	7,000	200	0	200	7,200	81
C-62nAreaMin	3,700	200	0	200	3,900	44
C-Title24	5,400	200	0	200	5,600	63
Fast Food						
62/2001	125,500	1,800	0	1,800	127,300	1018
62tracking	27,600	1,000	0	1,000	28,600	229
C-ZeroMin	46,300	1,300	0	1,300	47,600	381
C-25%Min	53,800	1,400	0	1,400	55,200	442
62n	30,700	1,000	0	1,000	31,700	254
C-62nAreaMin	5,500	800	0	800	6,300	50
C-Title24	41,900	1,200	0	1,200	43,100	345

Table A4 Detailed Energy Loads for San Francisco

	Heating (MJ)	**Sensible cooling (MJ)**	**Latent cooling (MJ)**	**Total cooling (MJ)**	**Total heating & cooling (MJ)**	**Total heating & cooling (MJ/m^2)**
Office						
62/2001	0	37,500	79,200	116,700	116,700	117
62tracking	0	29,200	56,100	85,300	85,300	85
C-ZeroMin	0	30,400	56,900	87,300	87,300	87
C-25%Min	0	31,700	61,500	93,200	93,200	93
62n	0	25,500	53,800	79,300	79,300	79
C-62nAreaMin	0	23,300	47,300	70,600	70,600	71
C-Title24	0	43,300	91,400	134,700	134,700	135
Conference Room						
62/2001	1,600	22,800	42,600	65,400	67,000	670
62tracking	100	5,200	9,400	14,600	14,700	147
62/Int	500	11,400	21,300	32,700	33,200	332
C-ZeroMin	200	8,100	14,500	22,600	22,800	228
C-25%Min	300	10,600	19,400	30,000	30,300	303
62n	200	7,100	13,200	20,300	20,500	205
C-62nAreaMin	0	3,100	5,600	8,700	8,700	87
C-Title24	200	9,400	17,200	24,600	24,800	248
Lecture Hall						
62/2001	4,300	62,300	127,700	190,000	194,300	1943
62tracking	1,400	25,500	52,100	77,600	79,000	790
62/Int	1,200	31,200	63,800	95,000	96,200	962
C-ZeroMin	2,000	37,400	74,900	112,300	114,300	1143
C-25%Min	2,300	41,600	83,900	125,500	127,800	1278
62n	1,200	33,200	68,100	101,300	102,500	1025
C-62nAreaMin	300	20,600	41,100	61,700	62,000	620
C-Title24	2,800	45,500	91,400	136,900	139,700	140
Classroom						
62/2001	700	12,900	27,000	39,900	40,600	406
62tracking	100	7,100	13,100	20,200	20,300	203
C-ZeroMin	200	8,300	15,100	23,400	23,600	236
C-25%Min	200	9,200	17,700	26,900	27,100	271
62n	600	11,600	24,200	35,800	36,400	364
C-62nAreaMin	100	8,300	15,800	24,100	24,200	242
C-Title24	200	10,200	19,600	29,800	30,000	300
Portable Classroom						
62/2001	400	6,500	12,600	19,100	19,500	219
62tracking	100	4,200	7,700	11,900	12,000	135
C-ZeroMin	100	4,500	8,100	12,600	12,700	143
C-25%Min	100	4,900	9,000	13,900	14,000	157
62n	400	6,600	12,800	19,400	19,800	222
C-62nAreaMin	100	5,100	9,600	14,700	14,800	166
C-Title24	200	6,100	11,400	17,500	17,700	199
Fast Food						
62/2001	7,200	65,200	162,000	227,200	234,400	1875
62tracking	1000	31,700	71,400	103,100	104,100	833
C-ZeroMin	1,700	41,600	95,300	136,900	138,600	1109
C-25%Min	2,100	45,200	106,200	151,400	153,500	1228
62n	1,500	35,300	87,600	122,900	124,400	995
C-62nAreaMin	200	25,200	59,500	84,700	84,900	679
C-Title24	1,600	40,300	94,300	134,600	136,200	1090

Table A5 Detailed Energy Loads for Miami

	Heating (MJ)	Sensible cooling (MJ)	Latent cooling (MJ)	Total cooling (MJ)	Total heating & cooling (MJ)	Total heating & cooling (MJ/m^2)
Office						
62/2001	47,100	7,300	8,500	15,800	62,900	63
62tracking	21,900	5,900	6,300	12,200	34,100	34
C-ZeroMin	22,300	6,400	6,600	13,000	45,300	45
C-25%Min	23,000	6,600	7,000	13,600	36,600	37
62n	7,600	5,000	5,800	10,800	18,400	18
C-62nAreaMin	2,700	4,700	5,200	9,900	12,600	13
C-Title24	75,300	8,400	9,800	18,200	93,500	94
Conference Room						
62/2001	63,300	4,600	4,800	9,400	72,700	727
62tracking	12,600	1,100	1,100	2,200	14,800	148
62/Int	30,900	2,300	2,400	4,700	35,600	356
C-ZeroMin	20,000	1,700	1,600	3,300	23,300	233
C-25%Min	27,600	2,200	2,200	4,400	32,000	320
62n	18,400	1,400	1,500	2,900	21,300	213
C-62nAreaMin	5,900	600	600	1,200	7,100	71
C-Title24	24,100	2,000	1,900	3,900	28,000	280
Lecture Hall						
62/2001	189,500	12,800	14,500	27,300	216,800	2168
62tracking	73,500	4,900	5,700	10,600	84,100	841
62/Int	90,400	6,400	7,300	13,700	104,100	1041
C-ZeroMin	107,300	7,400	8,400	15,800	123,100	1231
C-25%Min	121,800	8,300	9,400	17,700	139,500	1395
62n	97,100	6,800	7,700	14,600	111,700	1117
C-62nAreaMin	53,100	4,100	4,600	8,700	61,800	618
C-Title24	132,900	9,000	10,200	19,200	152,100	1521
Classroom						
62/2001	39,300	2,400	2,900	5,300	44,600	446
62tracking	17,300	1,400	1,500	2,900	20,200	202
C-ZeroMin	19,400	1,700	1,700	3,400	22,800	228
C-25%Min	22,700	1,800	1,900	3,700	26,400	264
62n	34,900	2,200	2,600	4,800	39,700	397
C-62nAreaMin	19,700	1,600	1,700	3,300	23,000	230
C-Title24	26,100	2,000	2,200	4,200	30,300	303
Portable Classroom						
62/2001	18,400	1,200	1,400	2,600	21,000	236
62tracking	10,700	800	800	1,600	12,300	138
C-ZeroMin	11,200	900	900	1,800	13,000	146
C-25%Min	12,500	1,000	1000	2,000	14,500	163
62n	18,800	1,200	1,400	2,600	21,400	240
C-62nAreaMin	13,500	1,000	1,100	2,100	15,600	175
C-Title24	16,400	1,200	1,300	2,500	18,900	212
Fast Food						
62/2001	241,200	12,100	18,100	30,200	271,400	2171
62tracking	91,400	6,200	8,300	14,500	105,900	847
C-ZeroMin	131,400	8,100	11,000	19,100	150,500	1204
C-25%Min	148,800	8,700	12,100	20,800	169,600	1357
62n	121,900	6,500	9,800	16,300	138,200	1106
C-62nAreaMin	72,400	4,800	6,800	11,600	84,000	672
C-Title24	128,700	7,800	10,800	18,600	147,300	1178

Table A6 Detailed Energy Loads for Minneapolis

Appendix B: PIER RFP Issues

The California Energy Commission (CEC) Public Interest Energy Research (PIER) Request for Proposals (RFP) for the Buildings Energy Efficiency Program Area identified four broad issues of key concern to the CEC. These four issues identify energy problems facing buildings in California and present opportunities to have a significant positive impact. This appendix will discuss the relationship of the application of CO_2-based DCV systems in small non-residential buildings to the four key issues based on information in this report.

Issue #1 Energy consumption is rapidly increasing in hotter, inland areas as new building construction increases in these areas.

Obviously, the primary intent of CO_2-based DCV systems are to reduce energy consumed to cool or heat ventilation air in buildings and, as demonstrated in this report, they are capable of achieving such reductions for many building types in a variety of climates. These results indicate that CO_2 DCV systems can reduce cooling energy consumption in the hotter, inland areas of California in many occupancies. As application of CO_2 DCV in new construction is considered, some thought will need to be given to the possibility that these newer buildings may have low infiltration rates during unoccupied periods and some strategy may be needed to address contaminant buildup when the system is off.

Issue #2 Development of energy efficient products and services needs to adequately consider non-energy benefits, such as comfort, productivity, durability, and decreased maintenance.

Since CO_2-based DCV systems directly affect ventilation rates provided in buildings, there is the potential to have a significant impact on building occupant comfort and productivity. That impact could be either positive or negative depending on the DCV system design, installation, operation and maintenance. CO_2-based DCV systems can have a positive impact on IAQ that is not commonly considered. Frequently, building zones are occupied by more people than the ventilation system design criteria. At such times, a DCV system will result in improved IAQ by increasing the ventilation supplied to the space. Additionally, ventilation systems may operate with lower ventilation effectiveness than the design criteria. Again, a DCV system can increase ventilation rates in such situations. While it is not possible to estimate potential impacts on productivity for any given building, Fisk and Rosenfeld (1997) have estimated that nationwide impacts of better indoor environments are in the billions of dollars.

Since DCV systems adjust ventilation rates based on measured concentrations of CO_2 generated by building occupants, they do not directly guarantee satisfactory indoor air quality (IAQ) due to the presence of non-occupant generated contaminants. This results in a concern by some that DCV could result in poor IAQ that would negatively impact comfort and productivity. Certain steps need to be taken to avoid the occurrence of such a negative impact. The most fundamental step is to implement the same good IAQ practices that should be applied to all commercial buildings. This includes such practices as reducing contaminant sources, properly installing and maintaining equipment, etc. Additional steps that should be taken for DCV systems include appropriate selection of control algorithms and setpoints, thoughtful consideration of expected contaminant sources, establishing needed minimum base and/or purge ventilation rates and schedules, and proper maintenance and calibration of CO_2 sensors.

Finally, the impacts of DCV systems on comfort and productivity have not been thoroughly studied. Since this is an important issue, more research in this area is needed.

Issue #3 Building design, construction, and operation of energy-related features can affect public health and safety.

The discussion above addressing Issue #2 applies equally to public health. CO_2-based DCV systems could have either a negative or positive impact on public health and care needs to be taken in their application. Specifically for moisture issues, DCV can have a very positive impact in lessening the moisture load in non-residential buildings in humid climates. Since most of the moisture load for many non-residential buildings is brought into a building through ventilation, reducing excess ventilation during times of reduced building occupancy can reduce this moisture load. This reduction in moisture load can save energy and money by eliminating the need for special equipment.

Issue #4 Investments in energy efficiency can affect building and housing affordability and value, and the state's economy.

As discussed in response to Issue #1, CO_2-based DCV systems can reduce building heating and cooling energy use and, therefore, reduce operating costs to improve building affordability and value. However, these potential savings will vary widely depending on building type, climate, occupancy density and patterns, other HVAC equipment used, and other factors. While knowledge of these important parameters is growing, more work is needed to identify the best opportunities for energy savings. No impacts are expected on the energy-related costs of construction.

Fisk, W.J. and A.H. Rosenfeld. Estimates of Improved Productivity and Health from Better Indoor Environments (1997) Indoor Air 1997; 7:158-172.