AN ABSTRACT OF THE THESIS OF

Andrew P. Silva for the degree of Master of Science in Environmental Health Management presented on December 2, 1997. Title: Analysis of Carbon Dioxide Levels in a Mechanically Ventilated College Classroom.

Abstract approved: ______________________________________
Anna K. Harding

Poor air quality can result in reduced productivity and higher absenteeism in students, fatigue, eye, nose and throat irritation and reduced comfort. The Occupational Safety and Health Administration (OSHA) estimates that 2 million education employees work in areas with poor indoor air quality.

The measurement of carbon dioxide often is used as a surrogate for defining adequate ventilation. Comfort (odor) criteria are maintained when carbon dioxide levels are below 1,000 parts per million (ppm).

The purpose of this study was to investigate a mechanically ventilated college classroom and to determine if carbon dioxide (CO₂) levels present a potential health risk to students. The following conclusions were drawn from this study. A strong association between occupancy numbers and CO₂ levels was found. Higher peak CO₂ levels occurred when more students were in attendance.

Rate-of-Rise (ROR) was strongly correlated to the number of persons
occupying the auditorium. This correlation held true when calculated for 10 minute, 20 minute and 30 minute ROR. As occupancy numbers increased, ROR also increased. ROR analysis was also found to be sensitive to previous occupancy numbers and more variance was explained when previous occupancy numbers were added in.

CO₂ levels exceeded the proposed OSHA regulations of 800 ppm 14 times during the study and exceeded ASHRAE’s 1,000 ppm guidance four times. When CO₂ levels did peak above 800 ppm limit, these levels were quickly reduced to ambient levels within a short period after class egress.

Although these CO₂ levels would not be expected to cause adverse health effects to persons using this auditorium, two episodes did occur when occupants were visibly uncomfortable from poor air quality conditions in the auditorium. One situation was due to the ventilation system being improperly in nonoccupancy mode, and the second situation occurred when a new screen was installed in the auditorium.

Finally, even though, the average occupancy number was less than half the capacity of the auditorium peak CO₂ levels in ECE, on occasion, did exceed those recommended by OSHA and ASHRAE which suggests that if the auditorium was filled to capacity, CO₂ levels would be considerably higher than those found during this study.
Analysis of Carbon Dioxide Levels in a Mechanically Ventilated College Classroom

by

Andrew P. Silva

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APPROVED:

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Dean of Graduate School

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Andrew P. Silva, Author
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ANALYSIS OF CARBON DIOXIDE LEVELS
IN A MECHANICALLY VENTILATED COLLEGE CLASSROOM

INTRODUCTION

Poor indoor air quality is affecting students in the United States' educational institutions (Fackelmann, 1990). Poor air quality can result in reduced productivity and higher absenteeism (Hansen, 1991) among students, fatigue (Godish, 1989), eye, nose and throat irritation, and reduced comfort (American Society for Heating, Refrigerating and Air Conditioning Engineers [ASHRAE], 1989). It can also cause severe health problems, such as asbestosis. Due to the aforementioned effects, poor indoor air quality may not be conducive to learning.

Indoor air quality is considered adequate in the college auditorium when 15 cubic feet per minute (cfm)/person of acceptable outdoor air is provided to the breathing space. This rate is a standard promulgated by the American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE, 1989). ASHRAE standards exist in many building codes, and are the basis for building ventilation designs and building ventilation rates. When met, these standards are designed to provide an acceptable indoor air environment, including thermal comfort, and at the same time conserve energy.

The measurement of carbon dioxide (CO₂) often is used as a surrogate for defining adequate ventilation (ASHRAE, 1989; Hansen, 1991; Woods, et al., 1989;
Bearth, et al., 1993). Comfort (odor) criteria are maintained when carbon dioxide levels are below 1,000 parts per million (ppm) (ASHRAE, 1989, USEPA, 1991).

Carbon dioxide is a colorless, odorless gas with a molecular weight of 44.01 grams (Baechler, et al., 1991). It absorbs energy in the infrared (Arnouldse, et al., 1992; Howard, et al., 1956; McCartney, 1983) and has an optimum absorption wavelength near 4.3 micrometers (Arnouldse, 1992).

Health effects from exposure to carbon dioxide vary with concentration (Baechler, 1991). The World Health Organization lists concentrations "of limited or of no concern" at less than 1,000 ppm and concentrations "of concern" as those greater than 6,700 ppm (World Health Organization [WHO], 1984).

Building occupants are reported to experience headaches, fatigue, eye and respiratory tract irritation when concentrations of carbon dioxide are at 1,000 ppm (Hansen, 1991). A study by Chow and Wang (1987) found a correlation between indoor air quality complaints in offices and carbon dioxide levels of 800-1,000 ppm.

Serious adverse health effects also are associated with high concentrations of carbon dioxide (Baechler, 1991). For example, pulmonary ventilation increases by 50 percent at levels of 20,000 ppm, 50,000 ppm creates dizziness, headaches and dyspnea, 80,000 - 100,000 ppm causes severe headaches, sweating, dimness of vision, tremors and loss of consciousness. Although carbon dioxide levels rarely reach these levels, adverse health effects are possible when other sources of contamination are combined with carbon dioxide levels above 1,000 ppm (Neuberger, et al., 1991).
The greatest contributor to indoor air concentrations of carbon dioxide are building occupants (Baechler, 1991). Gas stoves and portable kerosene and gas space heaters do contribute to indoor concentrations of carbon dioxide, but to a lesser degree. Typical occupant-generated, carbon dioxide rates for school-type work (1.2 Mets) is 0.36 liters per minute (l/m) per person (ASHRAE, 1989).

Ambient (outdoor) air concentrations of carbon dioxide range from 250 to 350 parts per million (ppm) (Hansen, 1991). Indoor air concentrations vary with building occupancy and outdoor air supply rates. Carbon dioxide concentrations are an indicator for the amount of fresh (ambient) air in a room, with higher levels of carbon dioxide indicating less ambient air inside a room.

Statement of Problem

A walk-through survey of auditoria on the Oregon State University (OSU) campus revealed situations of inadequate indoor air quality. A sampling of students and instructors complained of hot and stuffy conditions during class-time. The walk-through noted outside doors propped open, hot, stuffy and humid air, and body odor smells. These symptoms suggest carbon dioxide levels above 1,000 ppm.

There is little research in the literature on indoor air quality in the college auditorium. A study by Wang (1975) examined bioeffluents in an auditorium. This study used grab samples to measure compounds ranging from acetone to toluene including carbon dioxide. Wang found carbon dioxide levels in the auditorium built up
to 860 ppm during a lecture attended by 430 people. He also reported that during
exams, the rate at which carbon dioxide was produced increased 45 percent over carbon
dioxide rates that occurred during normal lectures. Another study of college auditoria
analyzed carbon dioxide levels and other chemicals found carbon dioxide levels to reach

Other research that has been done basically shows case studies of "sick" public
schools (Fackelmann, 1990; Neuberger, 1991), modeling of HVAC designs (Wheeler,
1992), mitigation and control (Godish, 1989; Nagda and Harper, 1989; Weekes and
Gammage, 1989; Hansen, 1991), and the use of carbon dioxide to indicate indoor air
quality.

Research that closely relates to a college environment involves a case study of a
public elementary school (Neuberger, 1991) and the modeling of an energy-saving
HVAC system (Wheeler, 1992). The study of the elementary school measured carbon
dioxide levels in various classrooms. These classrooms featured natural ventilation
with central hot water heating (not forced air). Carbon Dioxide levels were found to
increase to levels of 1,500-1,800 ppm as the school day progressed.

The HVAC modeling study also analyzed carbon dioxide levels in classrooms,
but its focus was more oriented at analyzing HVAC control systems, energy use and
modeling. Some recommendations from the study were to design HVAC systems to
meet ASHRAE Standard 62-1989, to correctly estimate the occupancy and to employ
demand controlled ventilation (e.g. HVAC switched by carbon dioxide monitors).
Purpose of Study

The purpose of this study was to investigate a mechanically ventilated college classroom and to determine if carbon dioxide levels present a potential health risk to students.

The following research questions directed the study:

(1) Is there an association between occupancy and carbon dioxide levels in a mechanically ventilated college auditorium?

(2) What is the rate-of-rise of carbon dioxide levels?

(3) Are carbon dioxide levels high enough to present a potential health risk to students? (This was based on ASHRAE 62-1989 and the proposed OSHA standard).

Study Objectives:

The following are objectives were also set forth:

(1) To design sampling strategy to determine carbon dioxide levels in a college classroom.

(2) To determine ambient air concentrations of carbon dioxide at a selected site on campus. This was an ideal classroom because it was possible to obtain average carbon dioxide levels and room occupancy numbers.
(3) To monitor carbon dioxide levels of in a classrooms over a two-week period.

(4) To monitor temperature (°F) in a classroom over a two-week period.

Definitions

Ambient air - Outside or outdoor air, usually, but not necessarily, contains the freshest, least contaminated air and is used to dilute building air.

ASHRAE - The American Society of Heating, Refrigerating and Air Conditioning Engineers. This group promulgates nonenforceable standards relating to building ventilation systems.

HVAC - Heating, Ventilating and Air Conditioning. A air handling unit that regulates the air inside a building.

IDLH - Immediate Danger to Life and Health. A condition that poses a threat of exposure to airborne contaminants when that exposure is likely to cause death or immediate or delayed permanent adverse health effects or prevent escape from such an environment.

NIOSH - The National Institute for Occupational Safety and Health. Basically the research arm for OSHA, NIOSH is responsible for recommending health and safety standards.

Occupancy - The partial or full filling of a given space with people.

OSHA - The Occupational Safety and Health Administration. OSHA promulgates and enforces standards for occupational settings.
OSHA - The Occupational Safety and Health Administration. OSHA promulgates and enforces standards for occupational settings.

Outdoor air damper - Louvers that control the percentage of outdoor air that is brought into an air handling system.

Return air - Air that is removed from a conditioned space by the air handling system.

STEL - Short-Term Exposure Limit. A 15-minute time-weighted average exposure that should not be exceeded at any time during a workday.

Supply air - Air that is brought into a space by an air handling unit to regulate the space’s temperature.

TWA - Time-Weighted Average. The TWA is measured over an 8-hour period unless otherwise specified by a substance-specific code.

VAV/VVA - Variable Air Volume or Variable Volume Air. A type of HVAC system that varies the amount of delivered supply air to regulate thermal conditions.

Limitations

There were several limitations of the experiment. Daily ambient carbon dioxide concentrations were not obtained during the experiment. These would have assisted in determining the efficiency of the ventilation system.
Daily ambient temperature levels were not obtained during the experiment either.

Observing the ambient temperature levels would have provided insight into the heating or cooling mode of the ventilation system.
LITERATURE REVIEW

The literature regarding the compound carbon dioxide and its use in determining indoor air quality (IAQ) in office buildings and K-12 schools, and research on effects associated with elevated levels, including health and performance effects, are discussed in this chapter.

Carbon Dioxide Standards

Carbon dioxide is normally a gas at room temperature and has a molecular weight of 44.01 grams. It is slightly heavier than air, is colorless and odorless and in its solid state is known as dry ice. World-wide, ambient levels of carbon dioxide range from 300 to 350 ppm (Hansen, 1991).

Industrial standards produced by NIOSH (National Institute for Occupational Safety and Health) and OSHA (Occupational Safety and Health Administration) stipulate that IDLH (Immediate Danger to Life and Health) conditions exist when carbon dioxide levels reach 40,000 ppm (NIOSH, 1994). This means that at IDLH conditions, an employee has sufficient time to immediately evacuate the area without being overcome. The short-term exposure limit (STEL), in which an employee can only be exposed for 15 minutes in one working day, is 30,000 ppm. The NIOSH and OSHA eight hour time-weighted average (TWA) is 5,000 ppm. By definition this
means that an employee can be exposed to an average amount of 5,000 ppm of carbon dioxide over an eight hour shift.

Carbon dioxide is evaluated differently in the nonindustrial, indoor environment. It is not compared just as an employee exposure against a set standard. Instead, carbon dioxide levels measured in an indoor environment indicate the rate of outdoor air being provided to the occupied space (ASHRAE, 1989, Bearg, et al., 1993). The greatest contributor to indoor air concentrations of carbon dioxide are building occupants (Baechler, 1991). If insufficient quantities of fresh, outdoor air are being provided to purge the occupied space, levels of carbon dioxide as well as levels of other contaminants will tend to be elevated. Carbon dioxide is an indicator of indoor air quality (Turiel, 1985), and "is the easiest way to tell if a school's fresh air rate is set too low" (Peck, 1994, pg. 33).

The American Society of Heating, Refrigerating and Air Conditioning Engineers (ASHRAE), which provides nonmandatory building standards designed to provide an acceptable indoor air environment, including thermal comfort, and while conserving energy, uses carbon dioxide in its evaluation of non-industrial, building ventilation systems (ASHRAE, 1989). As referenced in the ASHRAE 62-1989 standard, it is estimated that the typical, occupant-generated, carbon dioxide rates for school and office-type work (1.2 Mets) is 0.36 liters per minute (l/m) per person. ASHRAE concludes that indoor air quality is considered adequate in the college classroom when 15 cubic feet per minute (cfm)/person of acceptable outdoor air is provided to the
breathing space. This rate will maintain carbon dioxide levels at 0.1 percent or 1,000 ppm (ASHRAE, 1989).

ASHRAE proposed a new standard on indoor air quality (IAQ) in 1996. This standard, referred to as 62R, further defines roles and requirements such as operation and maintenance requirements for ventilation systems and source management (Burton, 1996). Also included are procedures for determining required airflow into spaces, which is divided into three procedures for “simple systems,” “prescriptive” and “analytical,” and a definition of air classes based on contaminant sources expected in the space. Classrooms with no unusual sources of contaminants are defined as “Class 1”.

OSHA went further than ASHRAE’s 1,000 ppm levels of carbon dioxide in its proposed IAQ standards for nonindustrial environments. This proposed standard was released in 1994 and advocated an indoor environment being kept below 800 ppm of carbon dioxide (Federal Register, 1994). OSHA received over 110,000 comments on the standard, the most ever, (Hooten and Laws, 1996) and has yet to formalize it as a standard (Lulay, Personal Communication, November 12, 1997).

Nevertheless, in terms of exposure, OSHA estimates that 2 million education employees work in areas with poor indoor air quality (Federal Register, 1994). They also estimate that roughly 94,000 school buildings suffer from poor IAQ. The Environmental Protection Agency (EPA) reports that one in every five schools has
high levels of radon gas (Knudson, 1993), which in some situations can be controlled by the ventilation system (Freije, 1989).

Health Effects

Health effects from exposure to carbon dioxide vary with concentration. Serious adverse health effects are associated with high concentrations (Baechler, 1991). For example, pulmonary ventilation increases by 50 percent at levels of 20,000 ppm, 50,000 ppm creates dizziness, headaches and dyspnea, 80,000 - 100,000 ppm causes severe headaches, sweating, dimness of vision and tremors with loss of consciousness occurring in 5-10 minutes.

It takes an enormous amount of carbon dioxide to be a direct threat to human health. In the indoor, office or school-type environments, carbon dioxide rarely reaches these extreme levels (Godish, 1989). Adverse health effects, however, are possible when other sources of contamination are combined with carbon dioxide levels above 1,000 ppm (Neuberger, 1991). This is because the other contaminants are not being diluted or flushed from the space. Many of the complaints associated with IAQ problems are irritation-oriented with the potential for harm (Godish, 1989).

Hansen reports that building occupants experience headaches, fatigue, eye and respiratory tract irritation when concentrations of carbon dioxide are at 1,000 ppm (Hansen, 1991). Chow and Wang (1987) found similar results with indoor air quality complaints (headaches, fatigue and irritation) in offices with carbon dioxide levels of
800-1,000 ppm. ASHRAE's comfort (odor) criteria are maintained when carbon dioxide levels are below 1,000 ppm (ASHRAE, 1989; USEPA, 1991). And, Greim and Turner (1991) say that carbon dioxide levels over 800 ppm is indicative of inadequate ventilation.

Inadequate ventilation has been reported in schools and universities throughout the United States, and consequently, there are a variety of health problems associated with poorly ventilated school environments. Rist (1991) discusses two different school episodes in her article. One school had sewer gas entrained into the building. It resulted in several students fainting. The other school had typical indoor air-oriented symptoms characterized by headaches, nausea, dizziness and numbness. Air sampling results found chemical levels below acceptable limits (based on OSHA industrial regulations) and were "not a danger factor to anyone." The symptoms were subsequently attributed to a variety of low-level contaminants in the building, which could be controlled by adequate ventilation (Rist, 1991).

Peck (1994) cites an elementary school having IAQ problems over a three-year period. Students and teachers complained of headaches, dizziness, allergies, musty odors and upper-respiratory tract distress. The School District contracted an Industrial Hygienist to sample the air, and they found that carbon dioxide levels were twice the recommended levels for classrooms. New ventilation units were installed, and the problem disappeared.
In another elementary school, an illness affected students and teachers (Reecer, 1988). The symptoms associated with the illness included hoarseness, smarting eyes, a facial flush and nausea. This school had been remodeled and had a new heating system. Officials were concerned that contaminants from a nearby oil company were entering the school, but testing was inconclusive. Eventually the Centers for Disease Control (CDC) and NIOSH were called in to investigate, but their testing was inconclusive also. They, however, did notice that teachers turned on and off their classroom’s unit ventilators quite frequently and, once this practice was stopped, the illness disappeared.

Still another elementary school had IAQ problems (Neuberger, 1991). These symptoms took on the typical characteristics of headaches, dizziness and nausea. The study found that inadequate ventilation, odors, and temperature/humidity control may have been the causative factors (Neuberger, 1991).

Performance and Liability

The Maryland State Department of Education outlines in its Indoor Air Quality report that poor indoor air quality affects the students ability to learn (Maryland State Department of Education, 1987). This also is reiterated in a paper prepared for the Association of School Business Officials that states that the poor air inside schools in America may inhibit student’s ability to concentrate on lessons (Andrews and Neuroth, 1988). Students also have shorter attention spans when
indoor ventilation is inadequate and the air quality is poor (Greim and Turner, 1991). Instead of being able to concentrate on their lessons, students in poor indoor air quality situations are more focused on their irritation-oriented problems such as itchy eyes, runny noses and headaches.

The Maryland State Department of Education report also states that poor indoor air quality may contribute to a higher risk of health problems and an increase in student and teacher absenteeism. In Wayne Hansen’s (1994) article *Something in the Air* he explains that a lot of the absenteeism is for doctor’s appointments for allergy treatments. His article states that these doctor appointments are to treat unspecified “maladies” attributable to IAQ problems. He continues with saying that absenteeism poses an additional threat to employers. IAQ problems decrease productivity and also decrease morale. They also increase employee turnover and increase employee medical-care costs (Hansen, 1994).

Liability issues also are associated with pollution in indoor air. Hansen (1994) says that many professional liability insurance policies have a pollution exclusion that is quite encompassing and a building owner (the University, for example) might not be protected. Building owners are ultimately liable in lawsuits regarding IAQ problems and even architects and designers are encouraged to protect themselves (Hansen, 1991). The building owner, which can be a school district or University, is also responsible for the repair and maintenance work of the facility. Failure to conduct proper maintenance on building systems, which could result in causing IAQ problems,
could eventually put the owner on the defensive in a lawsuit (Rotondo, 1993). This may be the case for the Salem/Keiser (Oregon) School District. As reported in the local paper, the Statesman Journal (McCullough, 1994), a teacher is suing the District claiming that IAQ problems made her ill and prevented her from working.

Employees made sick by their work environment can end up filing worker’s compensation claims. This usually is brought on by frustration in situations where there is no permanent relief from the IAQ problems (Hansen, 1994). Employees that are unionized also can file grievances and Hansen (1994) reports that grievances are a difficult and costly process for an employer. Employers with union employees may even find themselves negotiating contracts that have clean indoor air provisions in them. Unions are interested in protecting their membership, and at one community college, the right to clean indoor air was negotiated into a union contract (Yakima Valley College, 1990).

Negative publicity surrounding IAQ problems can be a real issue for employers, particularly those in the public sector. The study conducted by Neuberger et al. (1991), discussed the event where complaints as well as test results were shared with concerned parents. The test results from the study were not adequately interpreted for the audience an subsequently created, “an atmosphere of hysteria.” The hysteria ended up closing classrooms and transferring teachers and students to other schools, which might not have been necessary. Reecer (1988) also found a similar political atmosphere in her investigation of a school reporting IAQ problems.
She states that complaints by office workers suffering IAQ-related illnesses are alarming, but when schoolchildren and teachers are involved, the resulting concern becomes an outcry. These outcries can find themselves on the front page stories in local newspapers (McCullough, 1994).

Relevant Studies

There is little research in the literature on indoor air quality in the college classroom setting. One particular study of interest concerning colleges and IAQ is a Master's Thesis done by a Brock University (Canada) student. Questionnaires were used for this thesis to evaluate stress factors affecting faculty and students of a particular community college. In the results, indoor air quality was the number one stressor (73 percent) among the sites within the city (Grant, 1991). It, however, became the number two stressor when combined with the data from the suburban site questionnaires.

A study by Wang (1975) examined bioeffluents in an auditorium. This study used grab samples to measure compounds ranging from acetone to toluene including carbon dioxide. Wang found carbon dioxide levels in the auditorium built up to 860 ppm during one lecture attended by 430 people. The study did not discuss carbon dioxide levels found in smaller classes. Wang's study was more focused on rate of which bioeffluents were produced by occupants. He reported that carbon dioxide production rates were similar to those of a previous study conducted by Welch.
(1961), with the exception that during exams, the rate at which carbon dioxide was produced increased 45 percent over normal lecture carbon dioxide rates (Wang, 1975). Another study of college auditoriums analyzed carbon dioxide levels and other chemicals (Fanger, et al, 1988). This study found carbon dioxide levels to reach 510 ppm.

Several studies prescribe to measuring of carbon dioxide as an IAQ tool in a school setting. One involves a case study of public elementary school (Neuberger, 1991). This study measured carbon dioxide and other contaminants in various classrooms to discover if they were adequately ventilated. It was conducted in response to complaints from faculty and students. The classrooms of this school featured natural ventilation with central hot water heating (not forced air). Carbon dioxide levels were found to increase in closed room configurations to levels of 1500-1800 ppm as the school day progressed. Conditions were found to improve in these rooms when windows and doors were opened, even if the opening was small.

Another study which also measured carbon dioxide in classrooms attempted to model an energy-saving Heating Ventilation and Air Conditioning (HVAC) system, and less focused on determining occupant exposure (Wheeler, 1992). The HVAC modeling research studied classrooms with variable air volume (VAV) terminals and compared one type against a modified type. VAVs are similar to what terminals are used in the Electrical Computer Engineering (ECE) building on the Oregon State University (OSU) campus. Carbon dioxide sensors were located in the return air
plenum to obtain an average room sample. The study did not include actual carbon
dioxide levels, but did report the average difference of carbon dioxide levels between
the two modeling approaches. The study recommendations included designing HVAC
systems to meet ASHRAE Standard 62-1989 and to correctly estimate the occupancy
and to employ demand controlled ventilation (e.g. HVAC switched by carbon dioxide
monitors).

Another study that supports the taking of samples in the return air plenum
was conducted in an office-library building (Shaw, 1991). The study employed an
automatic manifold which sampled from the return air plenums of the ground, first,
third and seventh floors and the outdoor air intake. Levels recorded were in the range
of 340-440 ppm.

Two other carbon dioxide studies of interest were conducted in commercial
airliner cabins (Nagda, 1991), and in child day-care centers (Daneault, 1992). Nagda’s
(1991) study used length-of-diffusion detector tubes in their sampling of carbon
dioxide. The study found that carbon dioxide levels exceeded 1,000 ppm in 87 of the
92 flights with the average level being 1,500 ppm. Several flights recorded carbon
dioxide levels over 2,500 ppm. The study compared a steady state equation which
was used to predict carbon dioxide levels in aircraft to those measured by the
researchers. Though they found an association ($r = 0.45$) between predicted and
measured carbon dioxide levels, the measured results were twice those from the
predicted equation. Several reasons were given for the disparity between the two
results. They included reduced ventilation efficiency in aircraft and increased carbon
dioxide production rates among the passengers due to increased stressors involved
with flying.

Daneault's (1992) study of child day-care centers employed sample draw
tubes and an infrared gas analyzer in taking carbon dioxide samples. Sampling took
place during the winter months in Montreal. It was found that 90 percent of the 91
facilities studied exceeded 1,000 ppm carbon dioxide with 13 percent exceeding 2,500.
ppm carbon dioxide. Four variables were found to be independent predictors of
carbon dioxide levels. These were density of children in the center, electric heating,
absence of a ventilation system and building age. Levels of carbon dioxide were related
to the level of occupation and determining the occupant density was a method use to
standardize all the rooms for comparison purposes. The study reported that each
child per cubic meter increased the carbon dioxide level by 70 ppm. Electric heating
increased the mean level of carbon dioxide by 250 ppm, and was more common in
newer, possibly better insulated, buildings. Ventilation systems were found to
decrease carbon dioxide levels by 562 ppm, and building age was reported to decrease
carbon dioxide levels by 12 ppm per year. The study recommendation called for air
quality standards appropriate for day-care settings to be developed.
METHODOLOGY

Research Setting

The study took place in a college auditorium on the Oregon State University (OSU) campus in Corvallis, Oregon. The classroom, ECE 102, was located in the Electrical and Computer Engineering (ECE) Building. The ECE building was built in the late 1980s and serves a variety of functions including housing research laboratories, clean rooms, television classrooms, general classrooms and offices. ECE 102 is used only for classroom purposes. It is designed like an auditorium and contains arced rows of fixed tables and 114 seats.

Ventilation for the auditorium is provided by a centralized HVAC system which utilizes a "dual deck" system. The "dual deck" system utilizes separate hot and cold ducts, or decks, to supply variable volume air terminals throughout the building. Dampers at each terminal control both the mixing of hot and cold air and volumetric flow of air into the rooms. ECE 102 has a dedicated terminal which exclusively supplies the auditorium.

Constant air flow and pressure are maintained in the trunk lines, the hot and cold decks and at the terminal. A pneumatic thermostat in the auditorium regulates hot and cold air distribution into the terminal. It also regulates the flow from the terminal into the supply duct for the auditorium.
One 13 inch supply duct leaves the terminal and travels above a false ceiling into the auditorium. In the auditorium, the duct branches out into four 10 inch ducts, and eventually distributes the air through 14 slot diffusers in the auditorium.

The slot diffusers are rectangular boxes four feet long, six inches wide, and contain two 3/4 inch slots that run the entire length. The diffusers are mounted on the slotted, false ceiling, and can provide up to 150 cfm of air from each one.

Twelve of the 14 diffusers are located in three evenly-spaced rows which run from the entrance side of the room to the far wall. The additional diffusers are placed between those rows and are near the far wall. This configuration creates a negative pressure zone above the slotted false ceiling, and creates higher pressure on the far side of the auditorium. The auditorium air is effectively forced up from the breathing zone and moved towards the auditorium entrance.

The return air duct is located above the auditorium entrance and is opposite the high pressure zone. The auditorium air is drawn out of the auditorium and into a return air plenum. This plenum empties into the adjacent atrium. It is then recovered by the HVAC.

The HVAC operating ranges are set at predetermined levels and were adjusted when the system was installed. The system is controlled remotely, by computer, at the OSU Physical Plant office. Minimum cooling air flow to the terminal box is 420 cfm and the maximum amount of cooling air flow to the terminal box is 2100 cfm. Maximum hot deck airflow into the box is 750 cfm.
Outdoor air dampers, which control the amount of fresh air entering the system, are always opened to 100 percent. The 100 percent outdoor air is an adaptation to meet ASHRAE 62-1989 which was promulgated after the design of the building. The hot deck is composed of 100 percent recirculated air.

Monitoring Equipment

Monitoring of carbon dioxide was conducted through the use of a non-dispersive infra-red (NDIR) detector from Young Environmental Systems (YES). It has an operating range of 0-5,000 ppm. The detector consists of plastic case housing the computer and electronics, a light emitting diode (LED) readout, alarm lights, on/off switch and modem port. The sampling chamber sits on the top of the detector and is housed by a slotted plastic cover.

The detector tests air which is passively drawn into the sampling chamber. The detector exposes air in the sampling chamber to infrared (IR) radiation. IR radiation is released from one end of the chamber and passes through the air sample. Carbon dioxide in the sample absorbs and scatters certain wavelengths in the IR bandwidth. The remaining amount arriving at the end of the chamber is filtered and absorbed by a cell. A comparison is then made between the amount of carbon dioxide released and that which is read at the cell. This number is displayed on the LED readout and is stored in the computer's memory. The desired wavelength for measuring carbon dioxide in the infrared is 4.3 microns (Howard, 1956).
The carbon dioxide detector can be operated on battery or A.C. power. In an attempt to reduce errors associated with battery power, however, the study operated the detector only on A.C.

Procedures

Air current tests were conducted in the empty auditorium using Drager Air Current tubes. These tubes released visible smoke which drifted with the air currents in the auditorium. One tube was used to release smoke down rows three, five and seven at an estimated breathing zone height. Smoke movement was then observed.

The smoke exited the breathing zone in under one minute and travelled up through the slotted ceiling and collected above the release areas. Within two minutes the smoke noticeably travelled towards the return air plenum.

Prior to the detector's placement, preparations were made to make data collection easier. These included gaining access to ECE, storing needed items and prepping the detector.

The researcher was a former student worker of the Communication Media Center, and was, at the time of the study, assigned to work in the television studio adjacent to ECE 102. This gave the researcher 24 hour access to both the auditorium and the television control booth. The control room provided electricity for the detector, a secluded observation site for counting, video recording equipment to double check, ergonomically-correct chairs and storage for a Personal Computer (PC).
Prep work for the detector also took place in the TV control room. Part of this work was to establish a connection between the detector and the PC via DOS software. Once this was completed and consistently reliable, the datalogger memory was cleared and its internal clock was synchronized with the clock in ECE 102.

Calibration took place according to manufacturer's recommendation using a lab-certified carbon dioxide gas mixture of 909 ppm. The calibration blanket was fitted to the sampling chamber and the gas mixture was administered. Pre-test calibration was 910 ppm, and a bump test later confirmed the calibration.

The detector was placed above the slotted ceiling of ECE 102 at the opening for the return air plenum. Virtually all the air in the auditorium exited through this area and it was ideal for obtaining the average carbon dioxide level for the whole auditorium.

Continuous power for the detector came from the TV control room. A construction grade electrical cord was threaded through the control room's false ceiling, into the return air plenum, which empties directly into the atrium, and to the ECE 102 connecting duct. Both the control room and ECE 102 return air ducts share the same return air plenum. The room ducts are basically holes in the wall above the doorway (and slotted/false ceiling) with a sheet metal lining. The electric cord and detector were marked with signs that indicates an experiment was in progress and that the system should not be disturbed.

The detector could be seen through the slats of the ceiling in ECE 102. Black cardboard was strategically placed so the ventilation flow was not compromised and
students could not see the lights on the detector. The researcher, however, if positioned just right and standing on tiptoes, could verify the on/off status of the detector. The audible alarm was turned off.

Data downloading occurred on Tuesdays and Fridays, for a total of four times. Data collection started on Friday, April 15, 1994 and ended April 29, 1994.

Sampling Strategy

The sampling strategy included the following steps:

1) The ventilation flow was determined through the use of a Drager Air Current Tube. This information was useful in determining the exact placement of the CO₂ detector.

2) Ambient carbon dioxide concentrations was measured at a selected site outside the ECE building. Steps were taken to avoid building and exhausts which may artificially raise ambient carbon dioxide levels.

3) A baseline measurement of carbon dioxide in the mechanically ventilated classroom was established by collecting samples over the weekend when the classroom was not in use. Samples were collected from the same site to be used for the week-long measurements. Sampling rates for the carbon dioxide detector were adjusted to 32-second intervals.
4) Monitoring of the mechanically ventilated classroom began on Friday, April 15, 1994 and operated continuously, except for data downloads, for two weeks ending on April 29, 1994. The carbon dioxide detector was secured in place above the students' heads, at the opening of the return air plenum, and was set to sample at 32-second intervals. Measurements at the return air plenum provided an average level of carbon dioxide in the classroom.

5) The detector was calibrated before and after tests were conducted.
RESULTS

Sampling of carbon dioxide levels took place from 4/16/94 through 4/29/94. During that period, over 40,000 data points were collected. The following sections are a presentation of the results.

Baseline Measurements

Ambient air carbon dioxide levels were obtained in the afternoon of 4/16/97 outside ECE building. The weather conditions were sunny with a slight wind. Carbon dioxide readings registered 349 ppm.

Figure 1: Baseline measurements
Baseline carbon dioxide levels were measured Saturday and Sunday, April 16 and 17, 1994, when students were not expected to occupy the classroom. Carbon dioxide levels for the auditorium were maintained at ambient levels during both days with the exception of one occupation. This occupation, on April 16, was not listed on the auditorium schedule and came as a surprise. This increase and decrease of carbon dioxide levels was easily noted and provided direct evidence of auditorium usage. The researcher noted that when the auditorium was not in use, the carbon dioxide levels dropped back to ambient levels (See Figure 1).

Occupancy and Carbon Dioxide Levels

The auditorium was occupied 37 times during the sampling period, and occupancy numbers were obtained for 62 percent, or 23 of these occupancies (See Table 1). Several occupancies were unaccounted for due to scheduling conflicts and impromptu or unscheduled usage of the auditorium.

Attendance numbers ranged from 39 to 99 students with an average size of 62. The mode was 50 students, which accounted for 5 of the 23 recordings. The auditorium was never recorded at the full capacity of 114.

The Monday/Wednesday/Friday occupancies, which are 50 minutes long, accounted for the highest usage (22 occupancies) of the auditorium. Attendance numbers were not obtained for Friday 4/22 and Friday 4/29, however, carbon dioxide measurements suggest fewer occupancies with smaller occupancy numbers.
<table>
<thead>
<tr>
<th>Date</th>
<th>Day of week</th>
<th>Number of occupancies</th>
<th>Recorded occupancies</th>
<th>Average Occupancy Number</th>
<th>Occupancy Number Range (High/Low)</th>
</tr>
</thead>
<tbody>
<tr>
<td>4/18/94</td>
<td>Monday</td>
<td>7</td>
<td>5</td>
<td>58.8</td>
<td>81/44</td>
</tr>
<tr>
<td>4/19/94</td>
<td>Tuesday</td>
<td>2</td>
<td>2</td>
<td>65.5</td>
<td>86/45</td>
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<tr>
<td>4/20/94</td>
<td>Wednesday</td>
<td>4</td>
<td>4</td>
<td>53.8</td>
<td>55/50</td>
</tr>
<tr>
<td>4/21/94</td>
<td>Thursday</td>
<td>3</td>
<td>2</td>
<td>67</td>
<td>79/45</td>
</tr>
<tr>
<td>4/22/94</td>
<td>Friday</td>
<td>4</td>
<td>1</td>
<td>99</td>
<td>Na</td>
</tr>
<tr>
<td>4/25/94</td>
<td>Monday</td>
<td>4</td>
<td>4</td>
<td>46.5</td>
<td>50/39</td>
</tr>
<tr>
<td>4/26/94</td>
<td>Tuesday</td>
<td>3</td>
<td>3</td>
<td>66.3</td>
<td>87/41</td>
</tr>
<tr>
<td>4/27/94</td>
<td>Wednesday</td>
<td>5</td>
<td>0</td>
<td>Na</td>
<td>Na</td>
</tr>
<tr>
<td>4/28/94</td>
<td>Thursday</td>
<td>3</td>
<td>2</td>
<td>74</td>
<td>76/72</td>
</tr>
<tr>
<td>4/29/94</td>
<td>Friday</td>
<td>2</td>
<td>0</td>
<td>Na</td>
<td>Na</td>
</tr>
</tbody>
</table>

Table 1: Auditorium Occupancies

The Tuesday/Thursday occupancies, which are 80 minutes long, accounted for 11 uses of the auditorium. Of particular interest was an Anthropology class which proved to be the only televised class held in the auditorium during the sampling period. This class consistently had attendance numbers in the 80s.

Occupancy Numbers and Carbon Dioxide Peaks

In Figure 2 are the highlights of auditorium usage for 4/18 and 4/19. Monday, 4/18, appears to contain the most uncharacteristic usage of the auditorium, with three extra occupancies. The scheduling at O.S.U. typically has the same number of classes, at the same times, for all days of the week. No other day during the experiment had three unscheduled occupancies were.
Recorded occupancy numbers for 4/18 ranged from 44 to 81 students. Carbon dioxide peaks, for recorded occupancy numbers, ranged from 682 ppm (44 students) to 1,015 ppm (81 students), and the total range for carbon dioxide was from 318 ppm to 1,015 ppm.

Figure 2: Carbon Dioxide and Temperature vs. Time, 4/18/94 through 4/19/94

Note: 44 / 682 signifies 44 persons and 682 ppm carbon dioxide.

Tuesday, 4/19, exhibits a low peak near 9:00 a.m. This was due to students arriving and waiting for their first class meeting, which was rescheduled to Thursday.

Recorded occupancy numbers for 4/19 ranged from 45 to 86. Carbon dioxide peaks for the day were recorded at 1,076 (86 students) and 729 (45 students). The total range for carbon dioxide was from 333 ppm to 1,076 ppm.
Figure 3 shows measurements taken from 4/20 through 4/22. A highlight of Wednesday, 4/20, has a class getting out early at 9:10 a.m. Recorded occupancy numbers for the day ranged from 50 to 55 students, and carbon dioxide peaks included 650 ppm (55 students), 889 ppm (55 students), 872 ppm (55 students) and 842 ppm (50 students). Total carbon dioxide range for the day was from 333 ppm to 889 ppm.

Thursday, 4/21 is a characteristic usage for Tuesday/Thursday, though the last occupancy in the afternoon was never put on the schedule. Recorded occupancy numbers for the day ranged from 77 to 79 students. Carbon dioxide peaks for the recorded occupancy numbers were recorded at 762 ppm (77 students), 1,031 ppm (79...
students) and 73 ppm (unknown number). The range for carbon dioxide levels for 4/21 was from 333 ppm to 1,031 ppm.

On Friday, 4/22, occupancy numbers were not obtained for the daily classes. The graph shows carbon dioxide levels were lower during the day than for other days of this week which may suggest smaller occupancy numbers. Carbon dioxide peaks were measured at 558 ppm, 589 ppm and 635 ppm. The evening had an occupancy number of 99 students with a peak of 1,800 ppm (See Figure 4). This class occurred while the building ventilation system was in its rest cycle. The rest cycle is when the building ventilation system is turned to its nighttime settings and is an energy-saving

Figure 4: Carbon Dioxide and Temperature vs. Time, 4/22/94 evening class
(low ventilation) mode. Figure 4 demonstrates what occurs to carbon dioxide levels when the largest occupancy of the auditorium occurs while the ventilation was off. The delay in the dropping off of carbon dioxide levels occurred because there was no ventilation to the room and it took an extended period of time for the carbon dioxide to clear out. Carbon dioxide levels took over three hours to drop to ambient levels after the class dismissed, which was the highest peak of the study.

The smallest occupancy number (39 students) was recorded on Monday, 4/25 (See Figure 5). Recorded occupancy numbers ranged from 39 to 50 students and carbon dioxide peaks for these occupancies occurred at 589 ppm (34 students), 636 ppm.
ppm (50 students), 920 ppm (50 students) and 651 ppm (47 students). The total carbon dioxide range for the day was from 302 ppm to 920 ppm.

Recorded occupancy numbers on Tuesday, 4/26, ranged from 41 to 87 students with peaks occurring at 604 ppm (41 students), 870 ppm (71 students) and 951 ppm carbon dioxide (87 students). The total range for carbon dioxide was from 302 ppm carbon dioxide to 951 ppm carbon dioxide.

Occupancy numbers were not obtained on Wednesday, 4/27, but peaks of carbon dioxide occurred at 493 ppm, 620 ppm, 636 ppm, 653 ppm and 905 ppm (See Figure 6). The total range for carbon dioxide for the day ranged from 302 to 905 ppm.

Figure 6: Carbon Dioxide and Temperature vs. Time, 4/27/94 through 4/29/94

Note: Unk / 620 signifies unknown number of persons and 620 ppm carbon dioxide.
Figure 6 also shows measurements recorded on Thursday, 4/28, with recorded occupancy numbers ranged from 77 to 79 students. The peak carbon dioxide levels occurred at 683 (unknown number), 872 ppm (77 students) and 998 ppm (79 students). The total range for carbon dioxide for the day ranged from 318 ppm to 998 ppm.

Occupancy numbers for Friday, 4/29, the last day of sampling, were not obtained. As seen in Figure 6, the only occupancy of the day had a peak of 605 ppm carbon dioxide. The total range for carbon dioxide for the day was from 318 ppm to 605 ppm.

A scatter plot graph (See Figure 7) of peak carbon dioxide levels and known occupancy numbers suggests peak carbon dioxide levels and occupancy numbers may be correlated. Analysis indicated these two variables were correlated (r = 0.77).
Rate-of-Rise

The determination of the rate of rise (ROR) of carbon dioxide levels was computed as the slope of the carbon dioxide rise. The ROR was calculated by subtracting the carbon dioxide level at Time \(_1\) from the carbon dioxide level at Time \(_2\) and dividing by the total time over that interval. The rate of rise was computed for the first 10, 20 and 30 minutes of the auditorium occupancy.

\[
ROR = \frac{CO_2(t_2) - CO_2(t_1)}{t_2 - t_1}
\]

In Table 2 are the results of the rate-of-rise computations. The first 10 minutes of occupancy had the highest average ROR of 10.9 ppm of carbon dioxide per minute. The 20 minute ROR averaged of 8.2 ppm carbon dioxide per minute, and the 30 minute ROR averaged 7.2 ppm carbon dioxide per minute. These numbers are consistent with the daily graphs in that in there is a sharp rise at the beginning of the class, the ventilation system reacts, then the rise of carbon dioxide starts to slow.

The occupancy with 47 students exhibits a negative ROR. This may have been the result of decreasing carbon dioxide levels in a smaller class which had been preceded by a class with a larger occupancy.

The regression equations in Table 3 include the occupancy number as the independent variable (\(X_1\)) and \(Y\), the ROR, as the dependent variable. These are for each ROR. The second equations include the previous occupancy number as an additional independent variable (\(X_2\)). Previous occupancies were added to the regression analysis to determine if they had an effect on the ROR (See Table 3).
<table>
<thead>
<tr>
<th>Occupancy Number (* First Class of the day)</th>
<th>Previous Occupancy Number</th>
<th>10 Minute ROR</th>
<th>20 Minute ROR</th>
<th>30 Minute ROR</th>
</tr>
</thead>
<tbody>
<tr>
<td>39</td>
<td>50</td>
<td>1.5</td>
<td>0.8</td>
<td>0.5</td>
</tr>
<tr>
<td>41</td>
<td>0</td>
<td>7.9</td>
<td>7.1</td>
<td>4.7</td>
</tr>
<tr>
<td>44</td>
<td>Unknown</td>
<td>4.7</td>
<td>3.9</td>
<td>3.1</td>
</tr>
<tr>
<td>45</td>
<td>0</td>
<td>9.5</td>
<td>7.1</td>
<td>5.8</td>
</tr>
<tr>
<td>47</td>
<td>50</td>
<td>-7.9</td>
<td>-5.5</td>
<td>-2.6</td>
</tr>
<tr>
<td>50</td>
<td>55</td>
<td>1.6</td>
<td>1.6</td>
<td>1.1</td>
</tr>
<tr>
<td>50*</td>
<td>0</td>
<td>2.6</td>
<td>2.9</td>
<td>2.4</td>
</tr>
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<td>50</td>
<td>4.6</td>
<td>3.2</td>
<td>3.6</td>
</tr>
<tr>
<td>50</td>
<td>69</td>
<td>15.7</td>
<td>10.3</td>
<td>7.9</td>
</tr>
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</tr>
<tr>
<td>55</td>
<td>0</td>
<td>15.8</td>
<td>13.4</td>
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</tr>
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<td>69</td>
<td>44</td>
<td>10</td>
<td>5.2</td>
<td>5.9</td>
</tr>
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<td>71</td>
<td>87</td>
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<td>11.1</td>
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</tr>
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<td>72*</td>
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<td>20.4</td>
<td>13.4</td>
<td>8.9</td>
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<td>76</td>
<td>72</td>
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<td>0</td>
<td>18.9</td>
<td>11.9</td>
<td>7.9</td>
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<td>79</td>
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<td>81</td>
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<td>86</td>
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<td>12.1</td>
</tr>
<tr>
<td>87*</td>
<td>0</td>
<td>14.2</td>
<td>9.5</td>
<td>10</td>
</tr>
</tbody>
</table>

Table 2: Rate of Rise of Carbon Dioxide

<table>
<thead>
<tr>
<th>ROR</th>
<th>Regression Equation</th>
<th>$R^2$</th>
<th>$R$</th>
<th>Std. Error of $Y$ Est.</th>
</tr>
</thead>
<tbody>
<tr>
<td>10 Min.</td>
<td>$Y = 0.269X_1 - 4.651$</td>
<td>0.441</td>
<td>0.66</td>
<td>4.833</td>
</tr>
<tr>
<td></td>
<td>$Y = 0.272X_1 - 0.039X_2 - 3.765$</td>
<td>0.482</td>
<td>0.69</td>
<td>4.832</td>
</tr>
<tr>
<td>20 Min.</td>
<td>$Y = 0.229X_1 - 5.476$</td>
<td>0.358</td>
<td>0.60</td>
<td>4.913</td>
</tr>
<tr>
<td></td>
<td>$Y = 0.229X_1 - 0.044X_2 - 4.273$</td>
<td>0.414</td>
<td>0.64</td>
<td>4.817</td>
</tr>
<tr>
<td>30 Min.</td>
<td>$Y = 0.208X_1 - 5.429$</td>
<td>0.455</td>
<td>0.68</td>
<td>3.646</td>
</tr>
<tr>
<td></td>
<td>$Y = 0.208X_1 - 0.021X_2 - 4.863$</td>
<td>0.475</td>
<td>0.69</td>
<td>3.674</td>
</tr>
</tbody>
</table>

Note: $Y = \text{ROR}, X_1 = \text{Occupancy Number and } X_2 = \text{Previous Occupancy Number}$

Table 3: Regression Equation for 10, 20, 30 Minute Rate-of-Rise
Figure 8: 10 Minute Rate-of-Rise vs. Occupancy Number

Figure 9: 20 Minute Rate-of-Rise vs. Occupancy Number
Temperature and Carbon Dioxide

Both temperature and carbon dioxide levels were monitored during the sampling period. The ventilation controls for the auditorium were controlled by a pneumatic thermostat. Data from the experiment demonstrate that this control was effective in controlling the temperature. In the first week of the experiment, temperature range was from 68 to 76 degrees F and the second week had a range from 68 to 74 degrees F. Mean temperature for the first week was 73 degrees F with the mean temperature for the second week being 72 degrees F.
DISCUSSION, CONCLUSIONS AND RECOMMENDATIONS

This study continuously monitored a college classroom for a period of two weeks, between 4/16/94 and 4/29/94. Samples were taken of carbon dioxide levels and temperature. These values were then compared against recorded occupancy numbers for the classes. This chapter discusses the results including making conclusions and recommendations for further study.

Discussion

Baseline measurements taken at the beginning of the two week sampling period demonstrated that the ventilation system of the ECE building dropped carbon dioxide levels down to ambient conditions. In fact, the ventilation system did not allow any buildup during the week at all as can be demonstrated in Figures 1-6. Carbon dioxide levels, depending on whether there was a class immediately following, fell to ambient levels shortly after classes dismissed. Although Bearg et al.'s (1993) studies found that residual levels of carbon dioxide in some office buildings increase as the working week progresses, the results of this study did not show a buildup.

Noticeable decreases in carbon dioxide levels were evident as students left the auditorium. Substantial, downward spikes were recorded during peak auditorium egress because the datalogger was located over the main doorway and recorded the atrium air, which had lower carbon dioxide levels in it, being circulated back into the
auditorium and lowered the carbon dioxide levels. The spike became a useful tool in keeping track of when the class ended.

Situations that did not allow the almost-immediate and complete purge of carbon dioxide from the auditorium occurred when a class directly followed the previous one and when the ventilation system was in the evening, nonoccupancy mode (See Figure 4). Gauging from the results of this experiment, the building's 100 percent open, ambient air damper on the cold deck was effective in the reduction of carbon dioxide. This, however, may not be the case during the winter months when the hot deck, which is recirculated, is used more often.

Occupancy Numbers and Peak Carbon Dioxide Levels

When occupancy numbers and peak carbon dioxide levels were compared, the results showed that auditorium occupancy played a major role in the increase and peak of carbon dioxide levels. In Figures 2 - 6, occupancy numbers are given followed by a corresponding peak in carbon dioxide levels. All the peaks recorded during the sampling period match those of times when the auditorium was occupied. Peak carbon dioxide levels were higher than those recorded in Wang's (1975) study which achieved a peak of 860 ppm carbon dioxide with an occupancy number of 420 students in an auditorium and Fanger et al.'s, (1988) which found levels of 510 ppm carbon dioxide in an auditorium setting.
A scatter plot (See Figure 7) of peak carbon dioxide levels and occupancy numbers indicated that a relationship existed. Regression analysis was used and resulted in the equation $Y = 7.04X + 402.82$, where $X$ was the occupancy number and $Y$ was the peak carbon dioxide level. Plugging in zero for the occupancy resulted in the classroom having a carbon dioxide level of 402 ppm, which is higher than ambient conditions. The standard error of the estimate was 96.75 and might explain the higher than ambient level of carbon dioxide when zero students are in the room. Such a large standard of error indicates that there is quite a bit of variance in the regression equation (Portney and Watkins, 1993).

The $R^2$ value of 0.59 showed that the equation is moderately predictive and that 59 percent of the variance in peak carbon dioxide levels can be accounted for by knowing the occupancy number. The $R$ value of 0.77 shows that the variables are strongly correlated - as occupancy increases, carbon dioxide levels also increase.

Carbon Dioxide Rate-of-Rise

The determination of the carbon dioxide rate-of-rise (ROR) was conducted in this study by subtracting the carbon dioxide level at time$_2$ from time$_1$ and dividing by time$_2$ minus time$_1$. This equation gives the slope of carbon dioxide levels. The ROR was determined over 10, 20 and 30 minute intervals and coincided with the start of class. Passing time, the period between classes, was not figured into the equation.
Scatter plots of the rate-of-rise and the occupancy numbers (See Figures 8 - 10) suggested an association between these variables. Table 3 contains the equations generated from this analysis. Table 3 shows correlation coefficient values of $r = 0.66$ (10 minute ROR), $r = 0.60$ (20 minute ROR) and $r = 0.68$ (30 minute ROR). $R^2$ values for the equations show that slightly less than half of the variance in the ROR may be explained by the occupancy number. Much more of the variance was explained in these results than that reported in a child daycare study which compared carbon dioxide levels to occupant density Daneault et al. (1992). These researchers calculated occupant density by dividing the occupancy number by square footage of the space, reporting "a significant and independent predictor of carbon dioxide levels" with an $R^2$ value of 0.1275. The lowest $R^2$ value for the experiment in ECE ($R^2 = 0.358$) was nearly three times that of Daneault et al.'s (1992) results.

Standard error of estimate numbers were much smaller than the one generated from the analysis of the peak carbon dioxide levels and occupancy number. The small errors indicate that there is less variability in the ROR regression equations.

Only one occupancy in this experiment did not have a positive rate-of-rise (ROR) in carbon dioxide levels. The fourth occupancy on Monday, 4/25 (See Figure 5), had a negative ROR with 47 students following the previous occupancy of 50 students. An examination of the data for this occurrence showed a slight rise in carbon dioxide levels over the first few minutes followed by a downward slope throughout the rest of the occupancy. This phenomenon suggested that previous occupancy number
might have an effect on the rate-of-rise. For this reason, additional regression analysis was completed and previous occupancy numbers were incorporated into the equations (See Table 3). Previous occupancy numbers had only a small effect on the equations and corresponding $R^2$, R and standard error of estimate.

The effects caused by the previous occupancy numbers could not be seen in the coefficients of the regression equations. The coefficients for occupancy numbers changed only in the equation for the 10 minute interval while the other two remained the same. This suggests that the coefficients were reliable in the original equations.

The effect caused by the previous occupancy numbers could be seen in the constants of the regression equations, the $R^2$ and R values. The constants associated with the equations were lowered with the addition of previous occupancy. $R^2$ and R values increased with the addition of previous occupancy numbers. This data demonstrates that when previous occupancy numbers are added into the equation, correlation coefficient values increase as does the amount of variance explained by occupancy.

Health Effects

Levels of carbon dioxide seen in the study were well below the 5,000 ppm, eight-hour time-weighted exposure (TWA) set in the OSHA regulations (NIOSH, 1993). There were no auditorium levels that approached this level. The highest level,
1,800 ppm, occurred on Friday 4/22, when the ventilation system was in its night setting (See Figure 4). This situation was clearly uncomfortable for the students, and the researcher noted many people fanning themselves and wiping their brows.

Occupant-perceived, uncomfortable conditions such as these may have an effect on concentration and the ability to assimilate information presented in the classroom (Andrews and Neuroth, 1988).

The ventilation system for the auditorium provided sufficient outdoor air to keep carbon dioxide levels below the recommended ASHRAE (ASHRAE, 1989) level of 1,000 ppm for the majority of occupancies. There were only three occupancies during daytime operating conditions that peaked at or above this recommended level (See Figures 2 and 3). Two of these levels were obtained for the same Tuesday/Thursday class during the first week of sampling when the levels reached 1,076 and 1,031 ppm carbon dioxide. The occupancy numbers for these classes were 86 (4/19) and 79 (4/21). The other occupancy (See Figure 2) that exceeded 1,000 ppm recorded 81 people and had carbon dioxide levels of 1,015 ppm. Several sources in the literature (Hansen, 1991; Greim and Turner, 1991; Godish, 1989; Chow and Wang, 1987) report that irritation-oriented complaints are associated with carbon dioxide levels above 1,000 ppm. It is logical to think that the longer occupancy time, as Tuesday/Thursday classes are, is a factor in the peak of carbon dioxide (ie. because the occupancy was longer, the carbon dioxide had more time to reach its peak), but the
hour-long occupancy of 81 on Monday suggests that the occupancy number may have the greatest impact.

It appears that occupancy numbers in the upper 70, low 80 range may generate enough carbon dioxide to send carbon dioxide levels in the auditorium over 1,000 ppm. This was demonstrated on 4/19 and 4/21 when levels exceeded 1,000 ppm carbon dioxide with 79 and 81 people. On the other hand, there were several large occupancies (87, 77 and 72) that did not produce such levels. These occupancies occurred first in the morning and were affected by the early morning cooling of the building. The occupancies that had 71 and 69 people, and weren’t first in the morning, did not reach 1,000 ppm.

The regression equation for peak carbon dioxide levels and occupancy numbers ($Y = 7.04X + 402.82$) was used to determine the occupancy number at which carbon dioxide levels would exceed 1,000 ppm. An occupancy number of 85 people (with a range from 71 to 98 students) would produce a level of 1,000 ppm.

In terms of meeting measured standards for carbon dioxide, the air handling system for the ECE auditorium does a sufficient job of complying when dealing with the short occupancy times and smaller attendances seen during the sampling period. Full occupancy, however, would likely cause conditions that would exceed the ability of the ventilation system to maintain comfortability. The largest occupancies seen in this experiment, which were roughly 3/4 capacity, produced carbon dioxide levels over 1,000 ppm and was observed by the experimenter to be somewhat stuffy.
The OSHA proposed standards for indoor air quality have, to date, not been approved (Lulay, Personal Communication, November 12, 1997). Nevertheless, carbon dioxide in the auditorium was above the 800 ppm guidance 14 out of 37 times. Greim and Turner (1991) report that carbon dioxide levels over 800 ppm are indicative of inadequate ventilation. The intent of the standard is focused on discouraging long-term events above 800 ppm, but is not intended for short-term peaks. In general, ambient levels of carbon dioxide are achieved shortly after class is dismissed. This suggests that other contaminants are removed as well (Turiel, 1985).

Data was not obtained on occupant comfort and complaints. However, there was one instance in the sampling period that obvious irritation due to inadequate indoor air quality was observed. During the second week of sampling, a new projection screen was installed at the front of the auditorium. Off-gassing from this screen was detected within several feet of the screen. One instructor remarked about the odor early in the lecture, and as he continued his presentation his voice grew hoarse. After the lecture, he complained of a headache, throat irritation and a general ill-feeling. Allowing the screen to off-gas prior to installation or purchasing a screen that does not off-gas might have prevented this episode.

Temperature

Temperature was included in the qualitative analysis of the auditorium, and as shown in the daily graphs (See Figures 1 - 6), the rise and fall of auditorium
temperature rises and falls with that of carbon dioxide. This condition held true throughout the experiment.

It is difficult to say with certainty that temperature responded to occupancy before carbon dioxide. Estimations based on the daily graphs appear to indicate that temperature rose first. However, temperature data from the monitor was not included in the quantitative analysis. Temperature became important in the analysis of carbon dioxide levels when it was discovered that carbon dioxide peaks during the first morning occupancy were lower than similar sized occupancies recorded in the latter part of the day.

Straight analysis of the carbon dioxide data was unsuccessful in determining the reason. The examination of auditorium temperature revealed that the temperature dropped to approximately 68 degrees, the bottom of its range, around 6:00 am every weekday morning. This appears to be a computer-controlled event that prepares the auditorium/building for anticipated heat loads during the day. Since this was a springtime sampling period, cooling the building prior to occupancy and rise in ambient temperature makes good sense economically and operationally. However, a potential problem might occur when the system is in winter mode and the building is preheated prior to occupancy. The hot deck of ECE is comprised of 100 percent recirculated air and occupant-generated carbon dioxide from the previous day may not be completely purged. The auditorium could start at a higher level and quickly exceed desirable conditions upon occupancy. It would be interesting to see if this is true
during the winter months and what effect, if any, would it have on the carbon dioxide levels.

Monitoring temperature and carbon dioxide simultaneously was important to assess the quality of auditorium air. The range of temperature in this study was 68 to 76 degrees for the first week (4/18/94 through 4/22/94) and from 68 to 74 degrees the second week (4/25/94 through 4/29/94). Carbon dioxide’s range was from 318 ppm to 1,800 ppm during the first week and from 302 ppm to 998 ppm for the second week. Monitoring temperature alone did not reveal the tremendous fluctuations of occupant-generated carbon dioxide. For example, on 4/19 (See Figure 2) the temperature fluctuates from 68 to 76 degrees, its whole range, from 8 am to 12 pm. During this same period, carbon dioxide levels fluctuated from 340 ppm to 1,076 ppm.

On the other hand, monitoring carbon dioxide did not reveal the operating conditions of a temperature-controlled ventilation system. Together, at least in this experiment, they provide a very good picture of the dynamics of the auditorium.

Conclusions

The purpose of this study was to investigate a mechanically ventilated college classroom and to determine if carbon dioxide levels present a potential health risk to students. The following conclusions are drawn from this study.

A strong association between occupancy numbers and carbon dioxide levels was found. Higher peak carbon dioxide levels occurred when more students were in
attendance in the auditorium. In addition, levels of carbon dioxide rise with the filling
and fall with the emptying of the auditorium, and the auditorium did not appear to
build up carbon dioxide levels over the week.

ROR was strongly correlated to the number of persons occupying the
auditorium. This correlation held true when calculated for 10 minute, 20 minute and
30 minute ROR. As occupancy numbers increased, ROR also increased. ROR
analysis is also sensitive to previous occupancy numbers and more variance was
explained when previous occupancy numbers were added in.

Carbon dioxide levels exceeded the proposed OSHA regulations of 800 ppm 14
times during the study and exceeded ASHRAE's 1,000 ppm guidance four times.
When carbon dioxide levels did peak above 800 ppm limit, these levels were quickly
reduced to ambient levels within a short period after class egress.

Although these carbon dioxide levels would not be expected to cause adverse
health effects to persons using this auditorium, two episodes did occur when
occupants were visibly uncomfortable from the poor air quality conditions in the
auditorium. One situation was due to the ventilation system being improperly in
nonoccupancy mode, and the second situation occurred when the new screen was
installed in the auditorium. These situations could have easily been prevented.

Finally, even though, the average occupancy number was less than half the
capacity of the auditorium peak carbon dioxide levels in ECE did on occasion, exceed
those recommended by OSHA and ASHRAE which suggests that if the auditorium
was filled to capacity, carbon dioxide levels would be considerably higher than those found during this study.

Recommendations

Several recommendations can be made based on the observations and results from this study. The first and most important recommendation is to employ demand-controlled ventilation using carbon dioxide sensors as the control mechanism. This study revealed the tremendous fluctuations in carbon dioxide ranges over the course of a day while the temperature ranges for the same period were tightly controlled. In combination with thermal regulation by the pneumatic thermometer, carbon dioxide levels can be controlled and occupants will be thermally comfortable.

Second, to control acute episodes of occupant discomfort associated with new equipment that produces large levels of off-gasses, buying and/or installation procedures should be modified. Buying procedures for the University should incorporate the purchasing of equipment that does not off-gas. This could be difficult to accomplish, but nevertheless would be beneficial. For situations that could not be remedied by selective purchasing, installation procedures should incorporate a period where equipment could off-gas in an unoccupied, well-ventilated area.

Third, instructors and facilitators using the auditorium in the evening should be trained in the use of nighttime ventilation controls. ECE 102 and several other auditoriums on the University campus have timer switches that turn on the ventilation
systems for those rooms when the systems are in their nonoccupancy modes. The timer switches are inappropriately labelled and many people do not understand their function. This may be remedied by providing clear language on the switches, visible notices and possibly an inservice for instructors regarding the operation of the timed system.

The final recommendation is to perform more carbon dioxide sampling during months of colder ambient temperatures. Because ECE’s hot deck uses recirculated air, dilution air during winter months may be insufficient to keep carbon dioxide levels below 1,000 ppm.

In regards to future research, it might be useful to analyze the situations where smaller classes follow larger classes. There was one instance in this experiment where there was a negative ROR when a small class followed a larger one. Analysis should be conducted to determine the effect caused by this relationship. Future research also might include taking ambient temperature and carbon dioxide variations while sampling auditorium carbon dioxide levels. Obtaining the ambient temperature would be helpful in determining the status of the ventilation system as to whether it is trying to cool or heat the auditorium. The ambient carbon dioxide levels could aid in computing the efficiency of the ventilation system.


APPENDIX
Figure 1: Carbon Dioxide and Temperature vs. Time, 4/18/94

Note: Unk / 700 signifies unknown number of persons and 700 ppm carbon dioxide.
Note: 86 / 1076 signifies 86 persons and 1,076 ppm carbon dioxide.

Figure 2: Carbon Dioxide and Temperature vs. Time, 4/19/94
Figure 3: Carbon Dioxide and Temperature vs. Time, 4/20/94

Note: 55 / 650 signifies 55 persons and 650 ppm carbon dioxide.
Note: 77 / 762 signifies 77 persons and 762 ppm carbon dioxide.

Figure 4: Carbon Dioxide and Temperature vs. Time, 4/21/94
Note: Unk / 558 signifies unknown number of persons and 558 ppm carbon dioxide.

Figure 5: Carbon Dioxide and Temperature vs. Time, 4/22/94
Figure 6: Carbon Dioxide and Temperature vs. Time, 4/25/94
Note: 87 / 951 signifies 87 persons and 951 ppm carbon dioxide.

Figure 7: Carbon Dioxide and Temperature vs. Time, 4/26/94
Figure 8: Carbon Dioxide and Temperature vs. Time, 4/27/94

Note: Unk / 620 signifies unknown number of persons and 620 ppm carbon dioxide.
Figure 9: Carbon Dioxide and Temperature vs. Time, 4/28/94

Note: 77 / 872 signifies 77 persons and 872 ppm carbon dioxide.
Figure 10: Carbon Dioxide and Temperature vs. Time, 4/29/94