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Carbon Dioxide and Ventilation Rates

by
Glen A. Chamberlin, Darren B. Myers, James M. Jones, Peter Rojeski, Jr., and Harmohindar Singh

In many buildings, the occupants themselves are a major source of indoor air contaminants. Carbon dioxide (CO_2) is one common human-generated contaminant. ASHRAE Standard 62-1989 states that the CO_2 level in the indoor air should not exceed 1000 parts per million (ppm). The most common method used to remove such contaminants from indoor air is to bring outdoor air into a building through an air-handling system by mechanical ventilation. However, fresh-air ventilation entails heating or cooling of the outside air to acceptable levels for indoor thermal comfort—an energy-expensive process.

A system designed to respond to CO_2 levels by introducing fresh outdoor air into air-handling systems "on-demand" may provide the optimal balance between energy efficiency and indoor air quality (IAQ). This study investigated the relationship between ventilation rates and CO_2 levels and their interaction in maintaining healthy IAQ, reviewed current gas-sensing technologies, and concluded that further research in the incorporation of gas-sensing technologies into Army Heating, Ventilation, and Air-Conditioning (HVAC) systems is warranted.

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In many buildings, the occupants themselves are a major contaminant source. Carbon dioxide (CO_2) is one **common** human-generated contaminant. ASHRAE Standard 62-1989 states that the CO_2 level in the indoor air should not exceed 1000 parts per million (ppm). The most common method used to remove such contaminants from indoor air is to bring outdoor air into a building through an air-handling system by mechanical ventilation. However, fresh-air ventilation entails heating or cooling of the outside air to acceptable levels for indoor thermal comfort an energy-expensive process.

A system designed to respond to CO_2 levels by introducing fresh outdoor air into air-handling systems "on-demand" may provide the optimal balance between energy efficiency and indoor air quality (IAQ). This study investigated the relationship between ventilation rates and CO_2 levels and their interaction in maintaining healthy IAQ, reviewed current gas-sensing technologies, and concluded that further research in the incorporation of gas-sensing technologies into Army Heating, Ventilation, and Air-Conditioning (HVAC) systems is warranted.

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Foreword

This study was done for U.S. Army Center for Public Works (USACPW) and Headquarters, U.S. Army Corps of Engineers (HQUSACE) under Project 4A162784-AT45, "Energy and Energy Conservation"; Work Unit FE-X34, "Energy Systems Technology for Indoor Air Quality." The USACPW technical monitors were Christopher Irby and Dennis Vevang, CECPW-EM; the HQUSACE technical monitor was Frank Meisel, CEMP-ET.

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1 Introduction

Background

Air circulation rates in buildings constructed after 1960 were often designed to meet building codes or guidelines based more on energy conservation goals and thermal requirements than on health considerations. At the time, such designs were reasonable; the basic building envelopes in older structures typically allowed infiltration of generous amounts of outdoor air, which, when coupled with mechanically-introduced outdoor air and low pollutant generation from building materials, kept indoor pollutant levels low.

Building envelope design has become tighter over the last several decades, allowing less outdoor air into the building, and thereby trapping more pollutants in buildings from sources such as building occupants, building materials and furnishing, office equipment (e.g., copiers), etc. Depending on the pollutant, its concentration, and the sensitivity of affected individuals, indoor air quality (IAQ) can have serious adverse impacts on the health and productivity of building occupants. ASHRAE Standard 62-1989, "Ventilation for Acceptable Indoor Air Quality" (ASHRAE 1989a) defines acceptable IAQ as "air in which there are no known contaminants at harmful concentrations as determined by cognizant authorities, and with which a substantial majority (80 percent or more) of the people exposed do not express dissatisfaction."

In many buildings, the occupants themselves are a major source of many pollutants and contaminants. Carbon dioxide (CO_2), an odorless, colorless gas produced by human metabolism, is one common human-generated contaminant. ASHRAE Standard 62-1989 states that the CO_2 level in the indoor air should not exceed 1000 parts per million (ppm).

Generally, two methods are used to remove such contaminants from indoor air: (1) removing pollutants from the airstream by filtration, or (2) exchanging the polluted indoor air with cleaner outdoor air. Bringing outdoor air into a building through an air-handling system by mechanical ventilation has become a key element in controlling the level of pollutants such as CO_2 in buildings. Fresh-air ventilation entails conditioning (heating or cooling) of the outside air to acceptable levels for indoor thermal comfort. This air-conditioning inevitably expends energy, so that it is seldom practical to circulate 100 percent outdoor air. A typical air-handling system mixes enough outdoor air with indoor air so pollutant concentrations remain below an acceptable threshold to both reduce energy consumption and maintain acceptable IAQ. A system designed to respond to CO_2 levels by introducing variable amounts of fresh outdoor air into air-handling systems "on-demand" may provide the optimal balance between energy efficiency and good IAQ. Preliminary study is needed to investigate whether such a system is feasible and what possible impacts it may have if implemented in buildings occupied by the U.S. Army.

Objectives

The objectives of this preliminary study were to investigate the relationship between ventilation rates and CO_2 levels and their interaction in maintaining healthy IAQ, and to review the current state of gas-sensing technology to determine whether further research in the incorporation of gas-sensing technologies into Army Heating, Ventilation, and Air-Conditioning (HVAC) systems is warranted.

The overall objective of this research program ultimately is to improve the control of ventilation systems and guidance documents of the U.S. Army Corps of Engineers (USACE) to enhance IAQ in buildings occupied by the U.S. Army in the most energy-efficient manner.

Approach

A literature search was conducted in the following areas:

- CO_2 generation rates by human building occupants to provide a better understanding of how human occupants affect the CO_2 concentration in buildings
- past and present recommended mechanical ventilation rates to contextualize the current research effort
- available techniques to measure CO_2 to determine the applicability of such methods to HVAC systems to control ventilation rates and indoor CO_2 levels.

Scope

This preliminary conceptual study is meant to be the first step in longer-term research meant to improve IAQ in buildings occupied by the U.S. Army through demand-controlled ventilation. This report presents information required to make an informed decision on the applicability of demand-based, CO_2-controlled ventilation.

Mode of Technology Transfer

Information from this report will be incorporated into applicable USACE guidance documents and into four related PROSPECT courses. Results of this study will be published in military publications and scientific journals. Presentations are planned for Corps of Engineers and other military meetings.

2 Carbon Dioxide Generation by Humans

Oxygen is necessary for the metabolism of food for energy and to sustain life. The carbon and hydrogen in foods, generally categorized into carbohydrates, fats, and proteins, are oxidized to produce carbon dioxide and water as waste products.

The consumption of the body's fuel mixture of carbohydrates, fat, and protein can be directly related to the body's waste production. In quantifying the body's CO_2 production, a molar ratio of the volume of CO_2 exhaled to the volume of O_2 consumed, called the respiratory quotient (RQ), typically varies from 0.71 for a diet of 100 percent fat, to 0.80 for a diet of 100 percent protein, and 1.0 for a diet of 100 percent carbohydrates (ASHRAE 1989b; MacHattie 1960). An RQ value of 0.83 applies to a normal diet mix of carbohydrates, fat, and protein (Consolazio, Johnson, and Pecora 1963). Not only is the RQ value affected by the body's fuel mixture, but it is also influenced by the body's activity level and physical conditioning. The average adult will maintain an RQ of 0.83 for light or sedentary activities increasing to 1.0 for extreme, heavy exertion (ASHRAE 1989b).

Since metabolic energy production increases in proportion to exercise intensity, so too does the rate of oxygen consumption and CO_2 generation (Consolazio, Johnson, and Pecora 1963). The relationship between the RQ and physical activity level in MET (metabolic rate) units is linear (Figure 1).

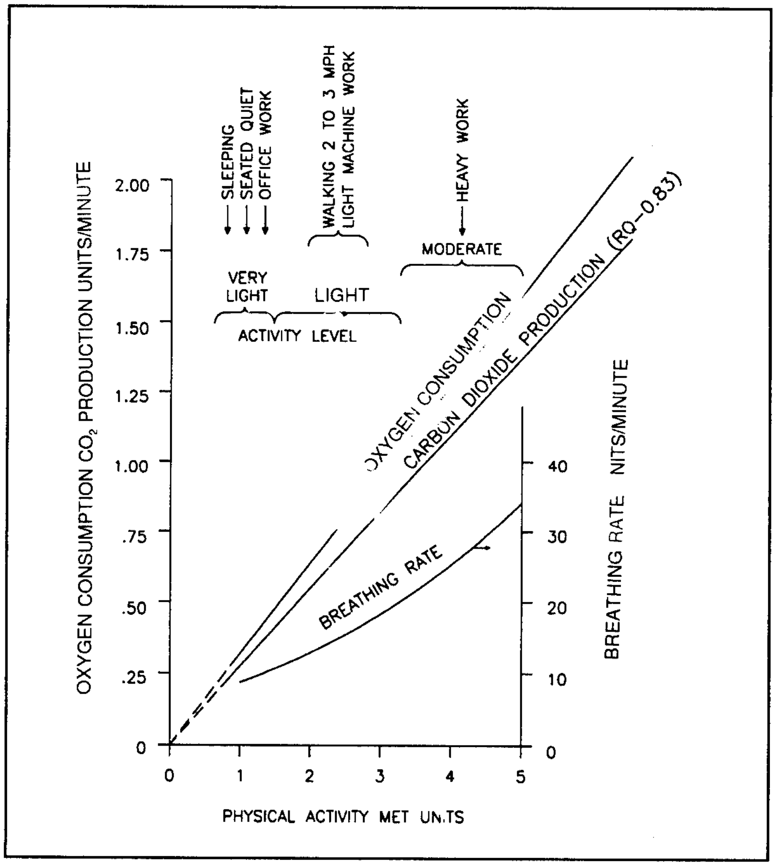

Figure 1. Metabolic data.

The MET is based on the metabolic rate of a sedentary person (seated, quiet) so that

1 MET = 18.43 Btu/hr sq ft = 50 k cal/hr m2 (Consolazio, Johnson, and Pecora 1963). The MET unit uses the average surface area of an adult person of 2830 sq in. (1.83 m^2) called the Dubois area (Ad). A normal, healthy adult male has a maximum energy capacity of approximately 12 at age 20, which drops to MET = 7 at age 70 (Consolazio, Johnson, and Pecora 1963). Maximum rates for women are 30 percent lower. Table 1 lists metabolic rates for an average adult, Ad = 2830 sq in., for continuously performed activities.

A person's MET rate can be related to the physiological components of respiratory oxygen consumption and carbon dioxide production by the empirical equation (Nishi 1981):

$$\text{MET} = 1200\,(0.23\,\text{RQ} + 0.77)\,\text{VO}_2/\text{Ad (Btu/hr sqft)} \qquad \text{[Eq 1]}$$

where:

RQ = Molar ratio of VCO_2 exhaled to VO_2 consumed

VO_2 = Volumetric rate of oxygen consumption at STPD conditions of 32 F, 14.7 psia* (L/min).

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* 1 psi = 6.89 kPa.

Table 1. Metabolic rates for prescribed activities.

	Energy Expended	
Activity	Btu/h × sq ft*	MET**
Resting		
sleeping	13	0.7
reclining	15	0.8
seated, quiet	18	1.0
standing, relaxed	22	1.2
Walking (on the level)		
0.89 m/s	37	2.0
1.34 m/s	48	2.6
1.79 m/s	70	3.8
Office activities	18	1.0
reading, seated	18	1.0
writing	20	1.1
typing	22	1.2
filing, seated	26	1.4
walking about	31	1.7
lifting, packing	39	2.1
Driving/Flying		
car	18–37	1.0–2.0
aircraft, routine	22	1.2
aircraft, instrument landing	33	1.8
aircraft, combat	44	2.4
heavy vehicle	59	3.2
Miscellaneous occupational activities		
cooking	29–37	1.6–2.0
house cleaning	37–63	2.0–3.4
seated, heavy limb movement	41	2.2
machine work		
– sawing (table saw)	33	1.8
– light (electrical industry)	37–44	2.0–2.4
– heavy	74	4.0
handling 50–kg bags	74	4.0
pick and shovel work	74–88	4.0–4.8
Miscellaneous leisure activities		
dancing, social	44–81	2.4–4.4
calisthenics/exercise	55–74	3.0–4.0
tennis, singles	66–74	3.6–4.0
basketball	90–140	5.0–7.6
wrestling, competitive	130–160	7.0–8.7

* Compiled from various sources; for additional information, see Buskirk (1960), Passmore and Durnin (1967), and Webb (1964).

** 1 MET = 18.43 Btu/h × sq ft

3 Calculating Outdoor Air Flowrate Requirements

The CO_2 concentration in a given space will vary depending on the number of people in the space, their physical activity, and outdoor air ventilation rate to the space. Indoor concentrations typically range from 500 to 2000 ppm or more. For a typical sedentary adult, exhaled breath will contain 2 to 3 percent CO_2 by volume (20,000 to 30,000 ppm), or 0.20 to 0.30 L/min. Outside levels of CO_2 range from 300 to 400 ppm (0.03 to 0.04 percent) (ASHRAE 1989a).

Through a two-chamber model (Figure 2), a mass balance equation can be solved to determine the outdoor air flow rate needed to maintain the steady state CO_2 concentration in a space below a given limit (ASHRAE 1989b):

$$V_o = N/(Cs - Co) \qquad \text{[Eq 2]}$$

where:

Vo = outdoor air flow rate per person (L/min)
Ve = breathing rate (L/min)
N = CO_2 generation rate per person (L/min)
Ce = CO_2 concentration in exhaled breath (%)
Cs = CO_2 concentration in the space (%)
Co = CO_2 concentration in outdoor air (%),

assuming a typical activity level of 1.2 MET units would give a CO_2 generation rate of 0.30 L/min/person (0.0106 cfm/person CO_2). If the maximum space concentration is to be held to 0.1 percent, 1000 ppm, and the outdoor concentration is 0.03 percent, 300 ppm, the outdoor air flow needed is:

$$\begin{aligned} Vo &= (0.30)/[(0.001 - 0.0003) \times 60\,\text{s/min}] \\ &= 7.0\ \text{L/s per person} \\ &= 15\ \text{cfm per person.} \end{aligned}$$

Figure 3 shows the relationship between required outdoor air flow rate, physical activity, and the steady state room concentration of CO_2 (ASHRAE 1989b). If the activity level is greater than 1.2 MET, increased outdoor ventilation is needed to maintain the same CO_2 levels.

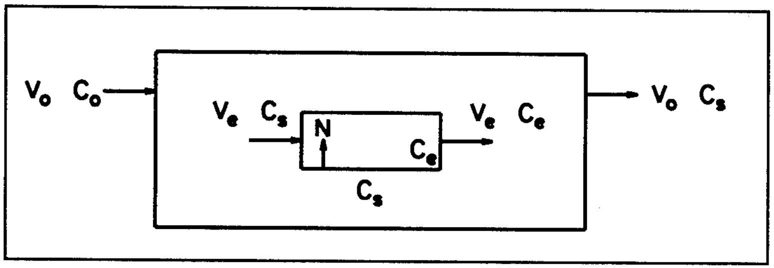

Figure 2. Two-chamber model.

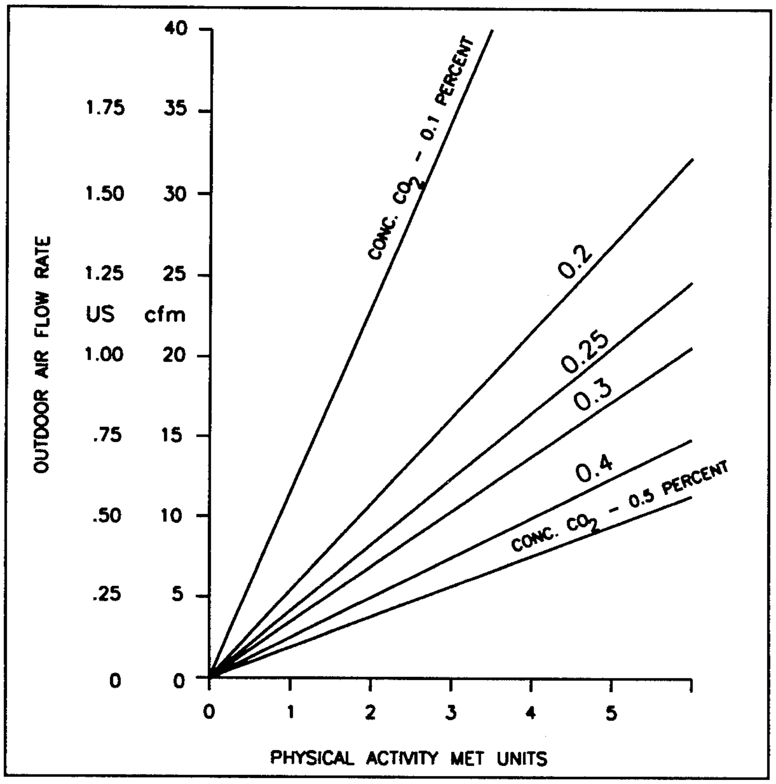

Figure 3. Ventilation requirements.

Decreasing oxygen content in a room can be modeled by substituting oxygen concentration for carbon dioxide concentration:

$$Cs - Co = N/Vo \qquad \text{[Eq 3]}$$

The value of N in Equation 2 has a negative value due to the consumption of oxygen as opposed to the generation of carbon dioxide in Equation 2:

$$Cs = N/Vo + Co \qquad \text{[Eq 4]}$$

To prove that dilution of CO_2 in a space is more significant than the addition of oxygen to that space, assume an activity level of 1.2 MET where oxygen consumption is 0.36 L/min. If ventilation is supplied to the space at a rate of 15 cfm/person (429 L/min), the room's oxygen level will be reduced from an outdoor concentration of 21 percent to a room concentration of 20.9 percent. This amounts to a total change in oxygen concentration levels of 0.5 percent. Meanwhile, the CO_2 concentration is raised from an outdoor concentration of 0.03 percent to that of 0.1 percent, an increase of 230 percent in CO_2 levels (Consolazio, Johnson, and Pecora 1963).

4 Historical Overview of Mechanical Ventilation Rates

The beginning of design for ventilation purposes dates back to the first compositions of architectural form and structure. Investigations into early architectural design show that the use of ventilation holes in roofs of dwellings and caves were required to exhaust pollutants from small indoor fires. The Romans first used window glazing in their building designs when they saw its advantages to indoor lighting and natural ventilation (Woods 1988).

Early concepts concerning standards for indoor air quality began in the 1600s when King Charles I of England instituted the earliest recorded regulation for ventilation control. In the Middle Ages, it was often noted that body, smoke, and combustion odors combined to make indoor air quality offensive. King Charles I specified that no house could be built with a ceiling height less than 10 ft (3.05m) and that windows had to be higher than they were wide (Winslow and Herrington 1949). By opening the top and bottom of the window, a natural circulation pattern could be achieved.

In 1824, Mr. T. Tredgold, a Welsh mining engineer, recommended minimum requirements of 4 cfm (2 L/s) of outdoor air per person for CO_2 control. Based on a concern for the spread of tuberculosis, Mr. T.S. Billings recommended in 1893 that 30 cfm (15 L/s) per person of outdoor air be considered a minimum ventilation rate for occupied spaces. He later stated that 45 to 60 cfm (23 to 30 L/s) per person of outdoor air was preferable. In 1895, these recommendations lead the recently organized American Society of Heating and Ventilation Engineers (ASHVE) to adopt 30 cfm per person of outdoor air as a minimum ventilation rate to reduce offensive indoor odors. By 1925, many U.S. states had included minimum ventilation rates in their building codes (Klauss et al. 1970).

In 1923, the New York state commission on ventilation concluded an 8-year study of school classrooms based on occupancy odor complaints. The original purpose of the test placed odor mitigation in the forefront of ideal ventilation conditions; it was decided that the majority of ventilation requirements would be based on grounds of human comfort rather than human health. The commission recommended a minimum ventilation rate of 10 to 15 cfm (5 to 8 L/s) per student for control of odor and CO_2

concentrations, allotting 250 cu ft (9 m^3) of space per student as a minimum design condition ("New York State Commission on Ventilation" 1923).

Further studies in the 1930s indicated a need for a minimum of 5 cfm (2.5 L/s) of outdoor air to maintain CO_2 concentrations below 600 ppm in extreme cases where a small number of people occupied a large space. As this volume of space per number of occupants ratio decreased, the subsequent ventilation rates per occupant increased logarithmically (Yaglou, Riley, and Coggins 1936). A majority of codes and standards used by designers for the last 50 years have been derived from this work (Woods 1988).

In 1946, the American Standards Association published the "American Standard Building Requirements for Light & Ventilation" (American Standards Association 1946), which dealt primarily with the natural means of providing light and ventilation, but also specified criteria, in cfm/sq ft, to relate requirements for personal ventilation to those of floor area and ceiling height. In 1973, the American Society of Heating, Refrigeration, and Air Conditioning Engineers (ASHRAE) revised and updated the Standard of 1946 with ASHRAE Standard 62-1973, "Standards for Natural and Mechanical Ventilation" (ASHRAE 1973).

This standard codified a comprehensive method of establishing ventilation rates. It emphasized ventilation air quantities in terms of volumetric air flow rates per person (cfm/person), introduced the concepts of using acceptable outdoor air for ventilation, and outlined the conditions under which outdoor air quality for ventilation could be improved by using the latest in recirculation and air-cleaning technology. As this standard was published, the oil embargo of 1973 had begun to affect the energy consumption in the United States. Although minimum and recommended values for ventilation design had been established, energy conservation efforts emphasized the minimum rates as specified in ASHRAE's energy conservation Standards, 90-1975 and 90A-1980. Thus, outdoor ventilation rates were effectively lowered. At this point, minimum ventilation rates were as low as 5 cfm/person while recommended, odor-free, comfort rates were typically 15 cfm/person. Note that, at this time, no mention was made of the makeup of indoor air quality (ASHRAE 1987). As better sealing of building envelopes reduced infiltration rates, and the use of construction, decorating, and furnishing materials that emitted chemicals increased, indoor air quality problems increased.

ASHRAE's energy conservation Standards 90-75 and 90A-80, "Energy Conservation in New Building Design," were expected to reduce energy requirements in new buildings by 15 to 60 percent by endorsing the minimum design values in ASHRAE 62-73 (ASHRAE 1975; 1980; 1987). These "conservation codes" were adopted by 45 states and also influenced codes in both Canada and Europe. The effects of these standards virtually eliminated the earlier recommended values and caused concern that the quality of indoor air in new buildings would be overlooked (Woods 1988; NCSBCS 1977; GPO 1976; Zegers 1980). This along with new developments in air quality research, dictated that Standard 62-73 be revised (ASHRAE 1987).

The new Standard, ASHRAE 62-1981, "Ventilation for Acceptable Indoor Air Quality," included two procedures with direct and indirect design implications to indoor air quality through outdoor air ventilation. A ventilation design procedure was rooted in energy conservation with implications for indoor air quality. The remaining indoor air quality design procedure permitted designers to use whatever amount of outdoor air they deemed necessary if they could show that the levels of indoor air contaminants were held below recommended limits (ASHRAE 1981). The 1981 Standard broke new ground by specifying acceptable levels of specific domestic and commercial contaminants. From the proceedings of the ASHRAE conference *IAQ 1987*, the term "contaminant" was used to indicate unwanted constituents that may or may not be trivial to human health, and the term "pollutant" was used to indicate the subset of contaminants that do present a potential human health risk (ASHRAE 1987).

ASHRAE 62-81 also listed required ventilation rates for smoking and nonsmoking areas rather than minimum and recommended values, although the typical values of 5 cfm and 15 cfm of outdoor air per person were maintained. Ultimately, some of the users of Standard 62-81 found the application of different ventilation rates for smoking and nonsmoking areas either confusing or difficult to implement in a design. This and other technological advancements in contaminant detection capabilities caused ASHRAE to authorize an early review of Standard 62-81 beginning in 1983 (ASHRAE 1989a).

In 1983, Leaderer and Cain measured how much environmental tobacco smoke (ETS) must be diluted to avoid the perception of smoke odor by people entering a smoking-allowed space. The study concluded that about 1800 cu ft (50.4 m^3) of smoke-free, outdoor air per cigarette was needed to satisfy 70 percent of the visitors. This equates with 30 percent of the occupants smoking at a rate of 1.7 cigarettes per hour with a ventilation rate of 15 cfm (7.5 L/s) of outdoor air per occupant.

Thayer (1982) compiled 41 data points from 10 different authors that considered occupants who had been in a smoking-allowed space for at least 15 minutes and had become desensitized to the ETS odor. Thayer devised an irritation index and a dilution index to quantify the responses to ETS. The study assumed a national average smoking rate of 1.1 cigarettes per hour per smoker with one-third of the population smoking. The investigation determined that a minimum of 15 cfm (7.5 L/s) per person outdoor air ventilating rate could control the amount of ETS in the space.

Also considered was that the ventilation rate for nonsmoking environments should increase from the minimum outdoor air ventilation rates from 5 cfm (2.5 L/s) per person to 15 cfm (7.5 L/s) per person. General discomfort, drowsiness, and increased perception of body odor had been observed at CO_2 concentrations greater than 1000 ppm (ASHRAE 1989a). Figure 4 shows some typical CO_2 levels experienced indoors and outdoors.

As the number of people or level of activity increase in a space, so will CO_2 concentrations. For example, with an activity level of 1.2 MET and outside air CO_2 concentration of 300 ppm, an inside CO_2 concentration of 1000 ppm in a 1000 sq ft (93 m^2) space occupied by seven people can be attained by supplying outdoor ventilation to the space of 15 cfm/person. Indoor CO_2 concentrations can be maintained at lower levels by increasing the outdoor mechanical ventilation rate. Figure 5 shows the higher mechanical ventilation rates that would be required to reduce CO_2 concentrations (Gaztech 1992b).

From this rose a natural concern for the energy penalty that would arise from the increased ventilation rates (Janssen 1989). Three studies done by independent researchers contributed to the ventilation standards established in ASHRAE 62-1989. A study done at Lawrence Berkley Laboratories calculated the energy penalties of raising ventilation rates from 5 to 20 cfm per person for typical office buildings located in 10 U.S. and three Canadian cities. The study concluded that energy operation costs rose around 5 percent on average, but under certain circumstances, rose as much as 50 percent (Eto and Meyer 1988).

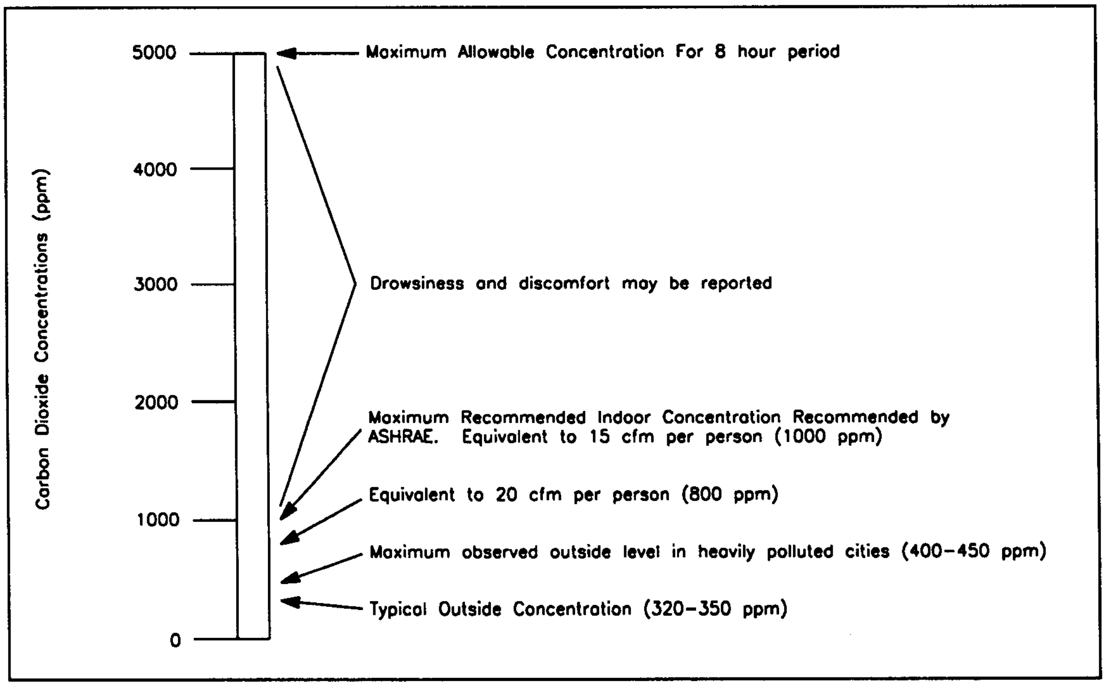

Figure 4. Comparison of CO_2 levels.

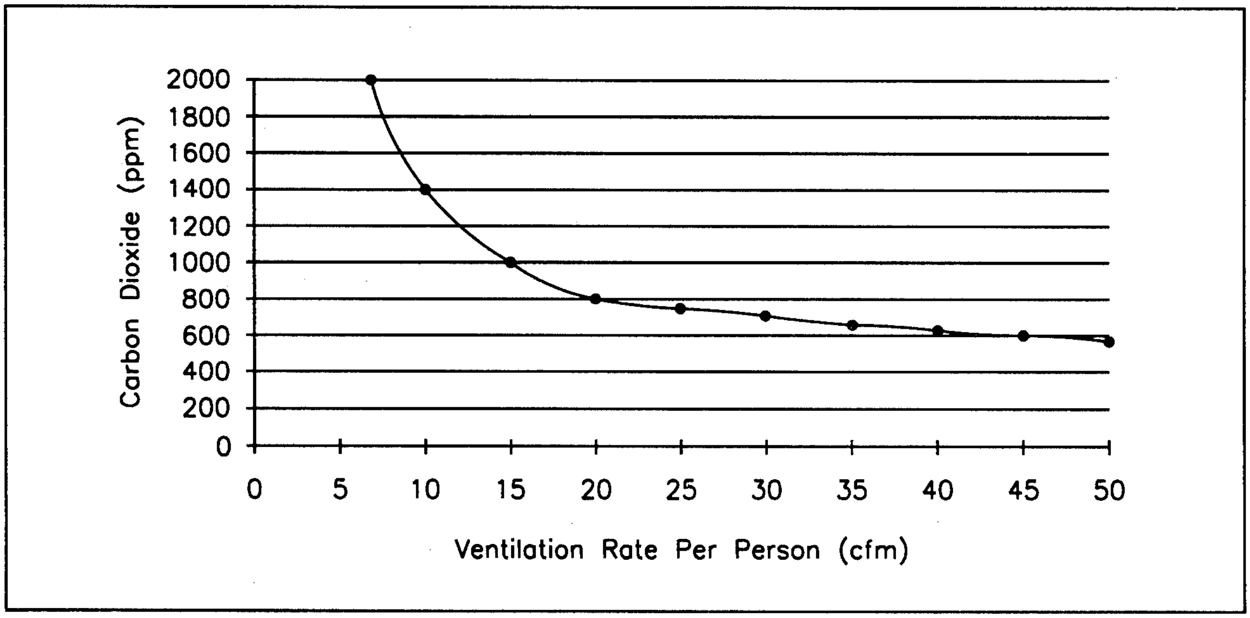

Figure 5. **Predicting ventilation rates (outdoor CO_2 level–300 ppm).**

Raising the minimum outdoor ventilation rate from 5 to 15 cfm per person for nonsmoking areas offered ASHRAE's Standards Project Committee (SPC) the opportunity to abandon the smoking/nonsmoking approach to acceptable ventilation. Also, considering the nation's decreasing smoking rate and increased separation of smokers and nonsmokers, there was a consensus within the SPC to establish the current outdoor ventilation rates below those of the smoking-allowed category included in the 1981 Standard. This allowed the combination of the two-tiered, smoking/nonsmoking table into one category of values (Janssen 1989). The new smoking lounge outdoor ventilation rate was established at 60 cfm (30L/s) per person in the 1989 Standard.

After many other studies, a new revised Standard was adopted in 1989: "ASHRAE 62-1989 "Ventilation for Acceptable Indoor Air Quality." The revised Standard retained the two procedures for ventilation design, the "Ventilation Rate Procedure" and the "Indoor Air Quality Procedure" (ASHRAE 1989a). The ventilation rate procedure is the indirect approach for controlling indoor air quality; it specifies the amount of outdoor air required to dilute and remove occupied space contaminants and pollutants to acceptable levels. The air quality procedure introduced in 1981 is a direct method for reducing contaminant levels in conditioned spaces. However, it does not specify the outdoor air requirements involved in applying this design format (Janssen 1989). The following chapter details ASHRAE Standard 62-1989.

5 Review of ASHRAE Standard 62-1989

Background

ASHRAE uses a consensus process to develop its voluntary standards. Specific care was taken by the SPC to include all concerned factions interested in standard construction and implementation in the writing of Standard 62-1989.

Although the Standard contains a Foreword, Body, and Appendices, only the body is the official Standard. The Foreword and the Appendices give background information and guidance. The user should be cautioned that code bodies might reference the entire document. Significant information within the Foreword and Appendices encompasses over half of the entire document. It is also important to note that the body of the document cross references the Appendices heavily. Thus, a thorough understanding of the Appendices is advised.

Foreword

The foreword states that "the conditions specified by this Standard must be achieved during the operation of buildings as well as in the design of the buildings if acceptable indoor air quality is to be achieved." This promotes a system of continuing design iterations that must be carried out throughout the life of the building.

The Standard states that "the goals of achieving acceptable indoor air quality and of minimizing energy consumption appear to imply a compromise." Recognizing that energy conservation and IAQ are compatible quantities is the first step to achieving balanced, healthy, and comfortable indoor conditions for the building occupants. This good design practice creates many opportunities to continuously upgrade and optimize building comfort and function. Also, note that "the Standard includes requirements for design documentation to be provided for system operation." Litigation considerations should motivate the designer to include documentation to properly commission the building.

Since the relationships between ETS, minimum outdoor ventilation rates, and possible adverse health effects had not been confirmed, the Forward of Standard 62-89 states that:

> For substantive information on health effects, the Standard must rely on recognized authorities and their specific recommendations. Therefore, with respect to tobacco smoke and other contaminants, this Standard does not, and cannot, ensure the avoidance of all possible adverse health effects, but it reflects recognized consensus criteria and guidance.

This disclaimer ensures that the document remains a design and *not* a health standard.

Body

The body is composed of six sections: purpose, scope, definitions, classification, systems and equipment, and procedures. The stated Purpose is to "specify minimum ventilation rates and indoor air quality that will be acceptable to human occupants and are intended to avoid adverse health effects." The Scope of the standard

> applies to all indoor or enclosed spaces that people may occupy, except where other applicable standards and requirements dictate larger amounts of ventilation than this Standard. Release of moisture in residential kitchens and bathrooms, locker rooms, and swimming pools . . .

Definitions

The user should already be familiar with most of the applicable definitions included in the Standard. However, special note should be taken of the following:

Acceptable indoor air quality: Air in which there are no known contaminants at harmful concentrations as determined by cognizant authorities and with which a substantial majority (80 percent or more) of the people exposed do not express dissatisfaction.

Air-conditioning: The process of treating air to meet the requirements of a conditioned space by controlling its temperature, humidity, cleanliness, and distribution.

Air-Ventilation: That portion of supply air that is outdoor air plus any recirculated air that has been treated for maintaining acceptable indoor air quality.

Occupied Zone: The region within an occupied space between planes 3 and 72 in. (75 and 1800 mm) above the floor and more than 2 ft (600 mm) from the walls or fixed air-conditioning equipment.

Classifications

The Standard specifies alternative procedures to obtain acceptable IAQ. The prescriptive ventilation rate procedure to air quality can be labeled as an indirect method for controlling IAQ that specifies the amount of outdoor air quality and quantity required to dilute and remove contaminants from the conditioned space.

The air quality procedure introduced in the 1981 Standard has been retained. Its effect on the indoor air contaminants is direct. The procedure requires the control of known, specific contaminant concentrations below acceptable limits. Outdoor ventilation rates utilized to achieve this procedure are left unspecified. However, if this procedure is used, design documentation should state this fact. Changes in the space use, space contaminant particles, or operation can require that the design be reevaluated.

Systems and Equipment

In the systems and equipment section, a number of significant points are covered including an accommodation for air flow measurement wherever a ventilation system is used. This provides for ample operating and diagnostic opportunities. "Ventilation air is to be supplied throughout the occupied zone." This is the breathing zone for the occupants and not the air handler alone. "Ventilating systems shall be designed and installed so that they do not cause conditions that conflict with ASHRAE Standard 55-1981, 'Thermal Environmental Conditions for Human Occupancy.'" Acceptable air quality is to be maintained at all times even when air supply is reduced to compensate thermal loads such as in Variable Air Volume (VAV) systems. Special care should be taken to avoid cross-contamination from sources such as cooling towers, sanitary vents, vehicular exhaust, loading docks and street traffic. Radon gas is flagged for special consideration. Radon undergoes radioactive decay with a half-life of 3.82 days into a series of solid, short-lived radioisotopes referred to as radon "daughters." These radon daughters become attached to suspended dust particles, which can be inhaled and stick to bronchial passages. Some radon daughters emit alpha particles, a short lived highly ionizing radiation that can damage cells, increasing the risk of lung cancer (Hansen 1991). The Standard states that "where soils contain high concentrations of radon, ventilation practices that place crawl spaces, basements, or underground ductwork below atmospheric pressure will tend to increase radon concentrations in buildings and should be avoided . . ."

Continuing along the lines of systems and equipment performance, ventilation distribution systems (ductwork) should be constructed and maintained to reduce fungal growth and dissemination of microorganisms. Localized contaminants must be collected and controlled close to the source for removal and treatment. Combustion systems should be vented outside of the building envelope. Sufficient make-up air is to be supplied to vented appliances and their related performance documented. Gaseous and particulate filters can be used to control contaminants. The user is cautioned to select the proper filter medium and efficiency depending on the contaminant source. Humidity should be regulated to between 30 and 60 percent relative humidity in the space. The Standard states that relative humidity above 70 percent in ductwork can produce ideal conditions for fungal contamination to grow. "Steam is preferred as a moisture source for humidifiers, but care should be exercised to avoid contamination from boiler water or steam supply additives." Avoid stagnant water in the HVAC system. Especially avoid entrapment of moisture from cooling towers.

In summary, ASHRAE Standard 62-1989 addresses a number of potential IAQ causes relating to maintenance, systems function, and equipment. It also encompasses areas such as: ventilation efficiency, adequate outdoor air supply to the occupants (even in a VAV system), maintainability (allowing the opportunity to access, monitor, test, and clean), avoidance of entrainment of contaminants in the air or fungal growth in the coils and duct work, the basic control of water that might promote microbiological growth, and the use of filtration to keep localized contaminant sources from the conditioned space.

Procedures

The Standard prescribes two procedures for achieving acceptable IAQ. The Ventilation Rate procedure uses tabular ventilation rates. Alternatively, the designer can apply the IAQ procedure introduced in the 1981 Standard. The IAQ procedure allows some latitude by controlling known and specific contaminants within the conditioned space. Additionally, if unusual or strong concentrations of contaminants are known at the time of design, use of the IAQ procedure can be performed to supply higher ventilation rates than set forth by the tabular material. Regardless of the selected procedure, it is imperative that the designer document the design criteria and assumptions. This documentation must be made available for commissioning the building.

Ventilation Rate Procedure

The traditional method for controlling air quality is by specifying outdoor air ventilation rates for specific occupied spaces. These rates are specified in ASHRAE Standard 62-89, Table 2. The tabular ventilation rates apply if there are no unusual contaminant sources present and if there is perfect mixing (Ventilation efficiency, Ve = 1.0). The procedure prescribes acceptable outdoor air for ventilation and outdoor air treatment when necessary. Standard 62-89, Table 2 lists ventilation rates for many types of commercial, institutional, residential, industrial, and vehicular conditioned spaces. Criteria are also referenced for reduction of outdoor air ventilation quantities when recirculation air is treated with contaminant removal equipment and criteria for VAV systems when the area in the conditioned space can be used to dilute the space contaminants.

This section also suggests procedures for evaluation outdoor air quality before it enters the building envelope. The ventilation rate procedure relies heavily on USEPA data such as that found in Standard 62-89, Table 1. Though not part of the Standard, the user is referred to the additional lists of contaminants shown in Appendix C if these contaminants are thought or known to be present. If acceptable outdoor air is not attainable, effective air-cleaning systems must be used to improve the outside air. If the cleaning technology is not accessible, outdoor ventilation rates may be reduced during peak periods such as rush hour, where high carbon monoxide levels are generated.

As mentioned before, Standard 62-89, Table 2 provides ventilation rates for over 80 types of conditioned spaces. Note that the minimum ventilation rate is 15 cfm/person. Most often, office space requires 20 cfm/person. Special use space such as smoking lounges require as much as 60 cfm/person. All of these specified outdoor ventilation volumes must be delivered to the occupied zone. Higher occupant levels in the conditioned space or poor ventilation efficiency may require increased ventilation above and beyond that of the rates recommended. All outdoor ventilation rates are specified to meet the required 1000 ppm concentration of carbon-dioxide. Though carbon-dioxide is not a problem itself until found in concentrations above 3500 ppm, it is a metabolic gas that can be an effective alert at levels above 1000 ppm. It can indicate occupant odor acceptability as well as indicate ventilation effectiveness in the occupied zone.

The Standard's Appendix F can assist the designing engineer with equations to help balance ventilation requirements to multiple spaces varying in usage. However, the 15 cfm/person rate specified in the Standard is the absolute minimum using the ventilation rate procedure. Intermittent occupancy can allow lower ventilation rates using the tables based on lag and lead time calculations included in Appendix G.

In Summary, the ventilation rate procedure will use the tabular ventilation rates given that acceptable outdoor air can be accessed. The designer must realize that the 15 cfm/person outdoor ventilation rate is an absolute minimum. If air cleaners are applied to reduce the contaminants in the return air to reduce the ventilation rates below those included in the ventilation rate procedure, then the IAQ procedure must be used. Assuming perfect mixing, the designer will achieve a Ve of 1.0 in the occupied zone. If bypassing occurs due to improper supply and return grill location, then Ve can drop as low as 0.5. This would require proportionate increases in outdoor air supply volumes. The user can refer to data in the Appendices to overcome these shortcomings in ventilation systems.

IAQ Procedure

A flaw in the ventilation rate procedure is that it assumes that contaminant generation and stratification will be reasonably similar from one building to another. However, there are many more contaminants created within the building envelope than those generated by the occupants, such as building-generated contaminants from adhesives, paints, etc. The IAQ procedure was developed to answer those uncertainties. Also, the IAQ procedure allows the user more design latitude by including the possibility of lowering ventilation rates by using air cleaners to treat return air.

To address the totality of the IAQ issue, the IAQ procedure incorporates both quantitative and subjective (qualitative) evaluations of the air quality. The quantitative evaluations must not exceed the "specified and acceptable" concentrations of contaminants that will provide acceptable IAQ. These concentrations may be achieved either by dilution with 100 percent outdoor air, or by dilution with outdoor air and some percentage of cleaned, recirculated air. Note that all contaminants known to the designer and owner, including those listed in Appendix C, must be reduced to required levels.

When such quantitative data are not available, subjective data must be collected and recorded by impartial observer panels. The subjective evaluations address those contaminants that cause unacceptable levels in physical stressor categories such as irritation of the eyes, nose, throat, and skin. "The evaluation is performed by a panel of 20 observers who must visit the occupied space under conditions of representative use and occupancy." At least 80 percent of the panel (16 of the observers) must find the air quality acceptable.

The measurement of contaminant concentration levels and subjective evaluations of those levels both occur after the design, construction, and occupation of the building. To predict the air quality at the design stage, a physical (mass balance) accounting must be performed in the same way as thermal or other loads are estimated. Appendix E may help the user with these calculations. Simple mass balance equations of the required ventilation rates, accounting for the contaminant, ETS, VOC, and bio-effluent generation rates, are the most direct way to determine outdoor air ventilation requirements. As with the ventilation rate procedure, contaminant concentrations, control assumptions, and filter-cleaning efficiencies should all be documented precisely.

Appendices

Though not part of the Standard, the appendices are heavily referenced as they contain supplemental material to aid and guide the user, including: conversion factors, positive combustion air supply, air quality criterion, carbon-dioxide concentration rationale, re-use of cleaned/ recirculated air, ventilation effectiveness, lag and lead time rationale, and unequal load rationale.

6 Gas Sensing Technology

Present day gas sensors are broadly classified into two basic types: “interactive” or “noninteractive” (Gaztech 1992a). Interactive sensors typically allow the sample to come into contact with one or more of the working components of the gas sensor such as electrolytes, sensing surfaces, electrodes, etc. Such contacts “sense” by oxidation, absorption, adsorption, etc. Noninteractive sensors are “noncontact” (Table 2).

Interactive Gas Sensors

The (Fuel Cell) Electrochemical Gas Sensor

Fuel cell, electrochemical gas sensors fall into two classes by the form of electrolyte used in the sensor. The electrolyte is most commonly in aqueous solution, but can also take a solid form such as porous, ceramic zirconium dioxide (ZrO_2). An electrochemical sensor with a ZrO_2 electrolyte is an excellent oxygen sensor due to this electrolyte's high conductivity for oxygen ions. The essential components of an electrochemical sensor set-up (Figure 6) are:

1. Two similar gas diffusion, fuel cell electrodes. One electrode, the counter electrode, is located deep within the cell interior. This restricts the diffusion potential from atmospheric gases. The remaining electrode, the sensing electrode, is placed so that it is readily accessible to ambient air gases.

Table 2. Gas sensor types.

Interactive	Noninteractive
Electrochemical fuel cell sensors a) aqueous or liquid electrolyte b) solid electrolyte	Nondispersive infrared (NDIR)-conventional gas sensors NDIR-photoacoustic gas sensors
Figaro or tin-oxide (SnO_2) sensors	
MOS metal-oxide-semiconductor sensors	
Catalytic (platinum bead) gas sensors	
Thermal conductivity gas sensors	

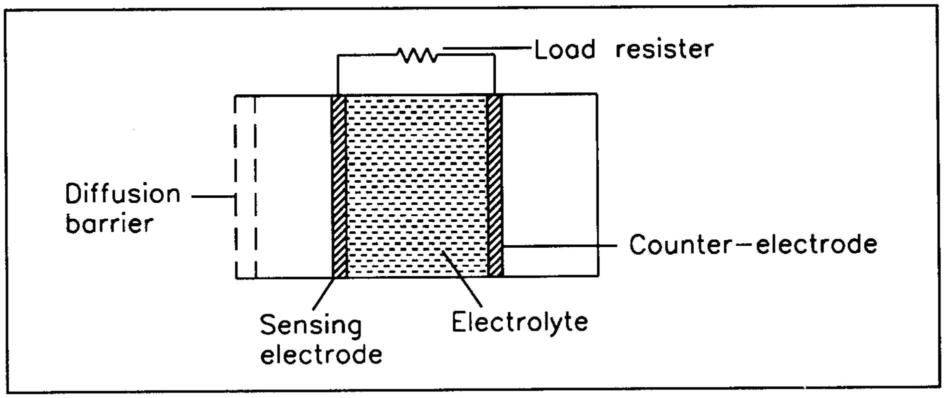

Figure 6. Elements of a (fuel cell) electrochemical gas sensor.

2. A concentrated, ionically conducting aqueous electrolyte separating the two electrodes (a solution of sulfuric acid or alkaline solution of sodium hydroxide).
3. A low impedance external electrical circuit connecting the sensing electrode and counter electrode and providing a voltage output across a load resistor to measure the current output of the cell.
4. A diffusion barrier controlling diffusion of reactant gases to the sensing electrode.

The electrodes in the sensor assume the same potential when no reactant gases are present. Thus, no current flows in the external circuit. If an electrochemically oxidizable gas, such as carbon monoxide, is present in the ambient air, it will diffuse to the sensing electrode first and cause its potential to shift in a cathodic direction. The resulting potential difference between the electrodes will cause a current to flow in the external circuit. The current, or output of the sensor, is caused by the electrochemical oxidation of the reactant gas at the sensing electrode, matched by an equivalent amount of oxygen reduction at the counter electrode.

An electrochemical fuel cell sensor with a solid electrolyte works similarly. The cells in this sensor are separated by porous ceramic ZrO_2 material that has a high conductivity for oxygen ions. The sensor samples combustion gases by monitoring the partial pressure of oxygen at the sampling electrode (lower pressure) and that of the reference cell (higher pressure usually atmospheric). When the fuel cell is kept at 1562 °F (850 °C), migration of oxygen molecules on the reference side will pick up electrons from the ZrO_2 surface, producing a voltage between the sample and reference sides of the ZrO_2 material. The voltage output of the sensor matches the oxygen content exposed to the sample side.

The Figaro (SnO_2) Sintered Semiconductor Sensor

The Figaro sensor (Figure 7) for measuring air contaminants or gases is based on the Taguchi Principle. The sensor is composed of a heated element inside a porous, semiconductive tube. The tube's surface can freely transfer electrons due to the differing energy levels of the reactant gas molecules and the semiconductor surface. Electron transfer occurs between the reactant gas molecules and the already absorbed oxygen molecules at the semiconductor's surface (Greystone 1992). The transfer of electrons from the semiconductor donor level to the layer of adsorbed gas results in decreased conductivity of the semiconductor.

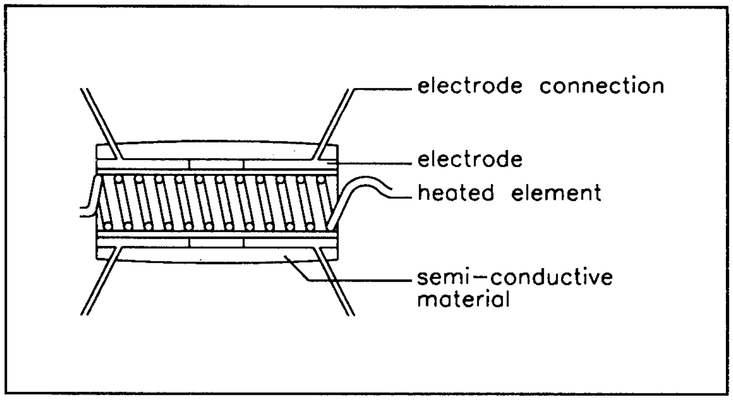

Figure 7. Figaro (SnO_2) sensor.

The semiconductor, formed by sintered powdered tin oxide (SnO_2), possesses a large number of grain boundaries between individual crystals. The adsorption of oxygen reduces the semiconductor's conductivity by quickly (within a few seconds) forming potential barriers at these grain boundaries. The reduced oxygen partial pressure decreases the further adsorption of oxygen molecules and increases the sensors conductivity (Gaztech 1992a; Greystone 1992). The rate of oxygen adsorption by the sensor is related to the temperature of the semiconductive-conductive material. Thus, the conductivity of the sensor maintained at a constant temperature in air will remain constant. However, when the sensor comes in contact with gases such as carbon monoxide, hydrogen, benzene, hydrocarbons, alcohols, etc., the molecules are adsorbed such that electron transfer occurs in a direction opposite to the oxygen reaction. This increases the migration of electrons to the semiconductor spacer charge layer, reducing the potential barriers at the grain boundaries formed by the already adsorbed oxygen. This increases the conductivity (reduces the resistance) of the sensor converting the concentration of the gases at the sensor surface to a sensor output (Gaztech 1992a; Greystone 1992, Geerts 1984).

Although the sensor responds to a wide variety of gases, including water vapor—not specifically to carbon dioxide—it is still quite useful in human environments. It should be noted that the Figaro sensor is highly sensitive to carbon monoxide and hydrogen gas (Gaztech 1992a; Geerts 1984).

The (MOS) Metal-Oxide-Semiconductor Gas Sensor

The metal-oxide-semiconductor (MOS) transistor produces an electrical signal dependent on the concentration of reactant gas present. The transistor modifies the

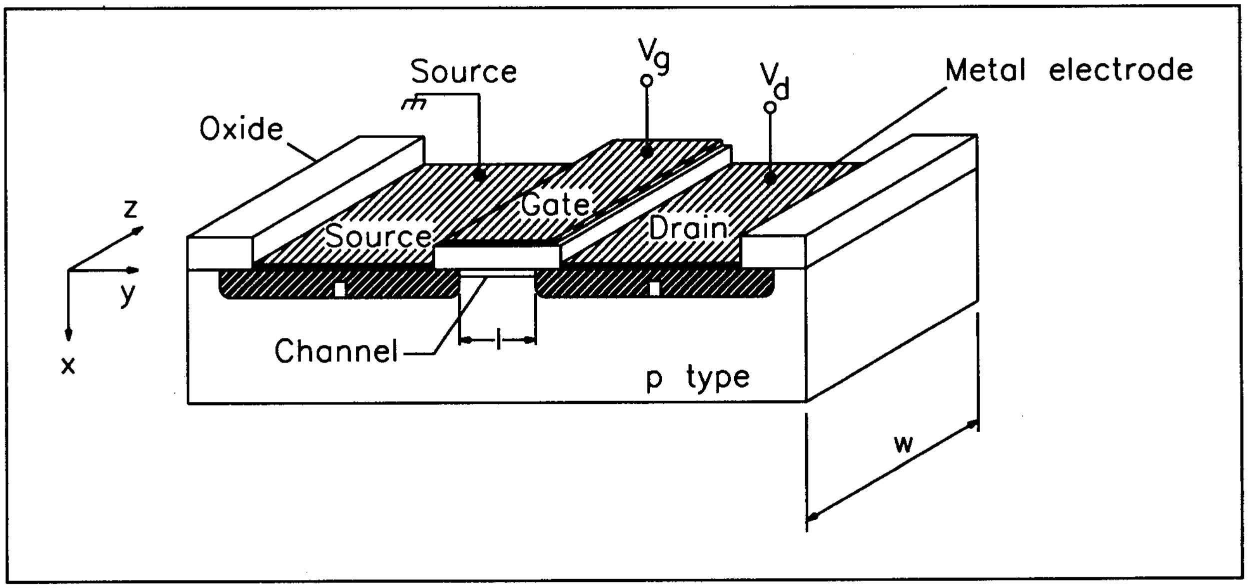

Figure 8. Metal-oxide semiconductor transistor.

conduction between the source and drain by a charge or potential created at the gate electrode (Figure 8).

The MOS sensor is basically a capacitor with the gate and the channel as electrodes. The charge on the gate induces a reflective charge in the channel, altering the conduction of the channel. Anything that alters the potential of the gate or the charge on the gate, such as the absorption or adsorption of gases, will alter the conduction of the channel, producing an electrical signal that can be processed (Gaztech 1992a).

A gas can either chemically react with the gate material and change the charge concentration of the gate or the gas can induce dipoles in the gate, altering the potential gradients at the gate-oxide interface. Finally, a chemical cell can form between the gate and the oxide (Gaztech 1992a). All of these mechanisms of sample gas interaction will have some effect on the potential or barrier height of the gate-insulator interface. Hence, the conductance of the channel itself is changed.

The gas-sensitive MOS sensor must be operated at elevated temperatures to function properly. A heater and thermal sensor must accompany the MOS sensor system. Many types of gates and dielectrics have been investigated. However, to date, no MOS sensor is completely specific to a particular gas molecule (Gaztech 1992a). A reliable sensor of this type requiring long-term stability and reproducibility has yet to be developed.

Catalytic (Platinum Bead, Wire) Gas Sensors

Most combustible gas sensors operate on the catalytic hot wire or bead principle. In the combustion chamber, a heated filament coated with platinum burns the flammable gas on its surface, raising the temperature of the filament. The filament's resistance increases proportionally to the temperature. The change in resistance can be measured in a wheatstone bridge circuit when a similar filament, without the platinum catalyst, forms the reference portion of the bridge. The observed change in resistance in the bridge is a measure of the percentage of combustible gas to ambient air (Gaztech 1992, Mine Safety 1992).

Thermal Conductivity Gas Sensors

Thermal conductivity sensors are based on the principle that different gases conduct heat differently. These sensors are generally accurate to within 50 ppm. As the composition of the sample gas changes, the cooling rate and wire resistance also change, giving an indication of gas composition. The thermal conductivity sensor suffers from slow response time, low sensitivity, and lack of repeatability. The thermal conductivity sensor is rarely used for accurate gas measurements (Gaztech 1992a).

Non-Interactive Gas Sensors

This method of gas sensing relies on the fact that most polyatomic gas molecules (such as CO, CO_2, SO_2, CH_4, etc.) have strong and very characteristic absorption bands in the middle infrared region of the electromagnetic spectrum (2 to 15 microns) (Gaztech 1992a). The atoms of a molecule are in constant movement, but because their movement is constrained by the inter-atomic bonds, the atoms vibrate to and fro in fixed vibration modes. These vibrations are at a certain frequency, called the "resonance frequency," which is determined by the mass of the atoms and the strength of the chemical bonds (Christensen 1991). The resonant frequency is constant for a given molecule.

The frequency of infrared radiation is of the same order of magnitude as molecular vibrations, approximately 10 to 13 Hz. Infrared radiation can interact with a molecule and transfer energy to it if, and only if, the frequency of the radiation is exactly the same as the resonant frequency within the molecule. When a molecule absorbs this radiation, it vibrates with greater amplitude, but at the original frequency (Christensen 1991). Thus, when light of a broad spectrum is passed through a gas, some of the frequencies are absorbed while the rest are transmitted without being absorbed. The amount of light absorbed is directly proportional to the concentration of the gas. Only those gases that, as a result of their vibrational or rotational motion, undergo a net change in electric dipole moment, can interact with infrared light (Christensen 1990, 1991). Single atom gases (i.e., Helium [He] and Mercury [Hg]) and homonuclear gases (i.e., oxygen [O_2] and chlorine [CL_2]) therefore cannot absorb infrared light.

When infrared radiation is absorbed by a molecule, the molecule gains energy and vibrates more vigorously. The amount of light energy absorbed can be observed by measuring either the heat energy released or the associated pressure increase. Both are proportional to the concentration of the absorbing gas molecules. Each substance has a unique infrared spectrum (Christensen 1991). The strength of the absorption is proportional to the amount of absorbing gas molecules. By calibrating with a standard sample of known concentration, the concentration of the suspect sample can be found. One of nondispersive infrared (NDIR) gas detection's strongest attributes is its ability to detect specific gases with little or no interference from other gases.

Conventional Non-Dispersive Infrared Gas Sensor

The NDIR method of gas analysis relies on a thin film narrow-bandpass interference filter for the wavelength selection of radiation. The passage of radiation through this filter is limited only to a narrow spectral extent (0.1 to 0.2 microns is typical), with the center wavelength coincident with the absorption band wavelength of the gas to be detected (Gaztech 1992a). All other wavelengths of radiation are rejected by this filter. Figure 9 shows how the NDIR technique works using the reference and signal channels. The reference channel is the optical branch where no change in the incident radiation occurs due to the gas absorption band being noncoincident with the center wavelength of the narrow bandpass filter. The signal channel is that optical branch where the presence of the gas to be detected causes a drop in the incident radiation at the detector due to the absorption of incident radiation by the gas (Gaztech 1992a; Christensen 1991).

A typical NDIR setup for gas measurement includes a high energy infrared heat source, a motor driven mechanical chopper for source light modulation, a pump to direct gas through the sample chamber, and a sensitive infrared detector (Figure 10). Expensive infrared optics are also required to focus the infrared energy from the source to the detector. The chopper allows for the synchronous detection of radiation from the source by the detector rejecting unwanted infrared energy from the ambient background (Gaztech 1992a; Christensen 1991).

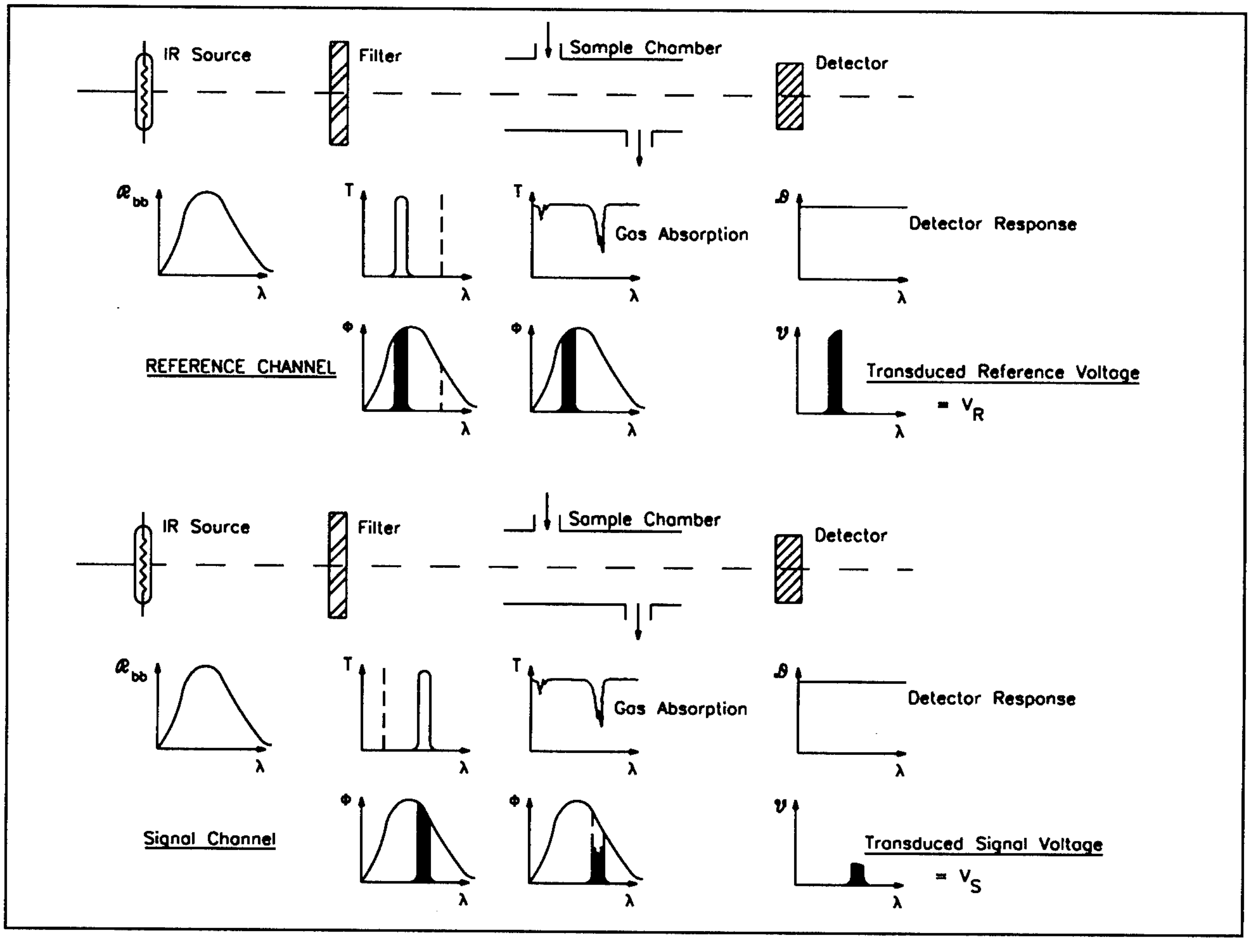

Figure 9. NDIR gas-sensing principles.

NDIR Photoacoustic Spectroscopy (PAS) Gas Sensor

The NDIR Photoacoustic gas sensor is identical to the conventional NDIR sensor in that it uses an infrared source and a thin film narrow bandpass filter to isolate the radiation wavelength to match that of the gas to be detected. The fundamental difference between the two techniques is the detection method. In conventional NDIR sensors, light is passed through the measurement chamber and the amount of light transmitted through the cell is measured by a light detector translating that light to a signal output proportional to the concentration of the measured gas. In PAS, the amount of light energy absorbed is measured directly by measuring the sound energy emitted when gas molecules absorb the infrared light energy. The phenomenon of the emission of sound by an enclosed sample on the absorption of chopped light is known as the Photoacoustic Effect (Christensen 1991).

The heat energy absorbed by a gas molecule is released as quickly as it was absorbed. This constant absorbing and releasing of heat energy increases pressure. When the incident light is modulated, or chopped, the pressure increase is periodic at the modulation frequency. Thus, the pressure waves, or sound waves, are easily measured

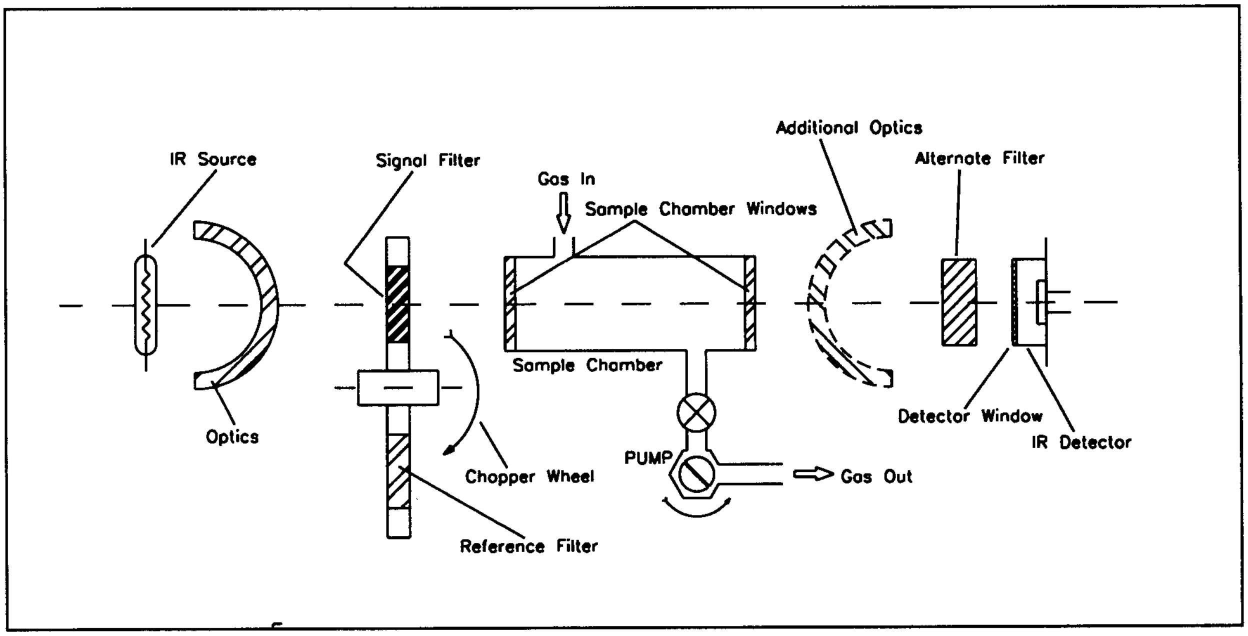

Figure 10. Conventional NDIR implementation.

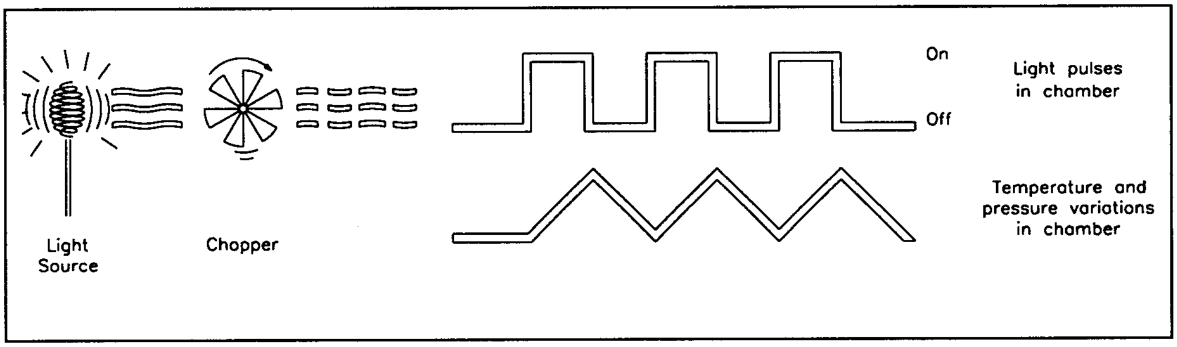

Figure 11. The photoacoustic process.

with a microphone (Christensen 1991) (Figure 11). The gas sample is sealed in the chamber. The chamber is irradiated with pulsed, narrow-band light. The gas absorbs light proportional to its concentration and converts it to heat. The gas heats and cools as it is chopped. Finally, the temperature fluctuation generates pressure waves that are detected by a microphone.

The essential components of a Photoacoustic sensor include a chamber to contain the gas sample, an infrared light source, some means of modulating the light (a chopper), a detector to measure sound (microphone), and a method of processing the signal. Figure 12 shows a schematic of a typical Photoacoustic sensor.

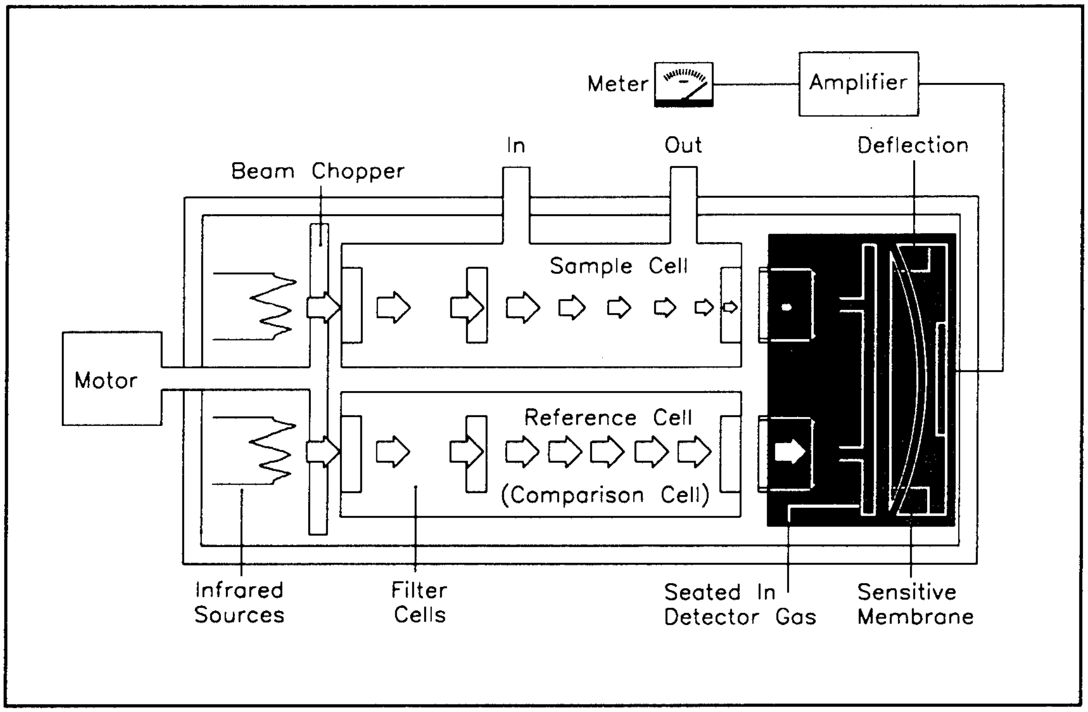

Figure 12. Photoacoustic gas sensor.

Comparison of Conventional NDIR vs. NDIR PAS

There are two methods of presenting the amount of light absorbed, either in terms of percent of Transmittance (Conventional NDIR) or in terms of Absorbance (NDIR PAS). The relationship between absorbance, A, and transmittance, T, of a gas at a particular wavelength is:

$$A = \log(1/T) \qquad \text{[Eq 5]}$$

In conventional NDIR, percent Transmittance is measured directly and substituted in the above equation to obtain absorbance. Any error in the measurement of T introduces an even greater error in the calculated absorption. NDIR PAS measures absorption directly with a very stable transducer (microphone) minimizing calibration. Typically PAS also uses a reduced volume of sample gas as compared to conventional NDIR (Christensen 1991). However, while NDIR PAS shares the attributes of stability and specificity with conventional NDIR, the lack of a pumping device in the sample chamber to purge the chamber after high sample concentrations are detected slows the response time. The NDIR PAS sensor is also quite temperature and pressure sensitive. The two methods do not possess any inherent advantages over one another, but the NDIR PAS sensor is generally more costly to build (Gaztech 1992a).

7 Summary and Recommendations

Studies have shown a relation between the CO_2 level in buildings and indoor air quality complaints, and also that the occupants themselves are a significant source of CO_2. These CO_2 levels can be predicted based on occupants' activity, gender, and other factors, which can together be used to determine air ventilation requirements. Typically, buildings are ventilated with cleaner outside air to reduce the CO_2 levels in occupied spaces.

While outside air ventilation recommendations and requirements have varied over the years, the current rate for office spaces is 20 cfm per person, based on a maximum concentration of 1000 ppm of CO_2. This rate was established in 1989 by ASHRAE Standard 62-1989, which specified a fourfold increase over previous outside air requirements. Subsequent studies have shown a 5 to 50 percent increase in energy consumption due to conditioning of increased outside air amounts, with the larger increases occurring in hot humid areas such as the southeast United States. Ventilation rates are usually established at a fixed rate based on an expected maximum building occupancy. Thus, a building occupied by fewer than the maximum number of occupants would be overventilated and, as a result, would consume more energy than needed.

A review of sensor technology reveals that currently available CO_2 sensors could be incorporated into HVAC control systems to vary the amount of outside air "on demand," based on the concentration of CO_2 in an occupied space. In buildings where the occupants are the major contaminant source and where the level of occupancy varies, ventilation rates could be varied to save energy in much the same way a thermostat conserves energy by regulating the circulation of heated air.

Based on this energy-saving potential, it is recommended that:

1. Currently available gas sensors should be evaluated to determine if they are accurate and reliable enough to be used on Army buildings.
2. A control scheme to incorporate these sensors, along with specifications and design drawings, should be developed.
3. Buildings that would benefit from a demand-based variance of the outdoor air ventilation rate should be selected to test energy usage reductions.

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