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INDOOR AIR QUALITY ISSUES RELATED TO THE ACQUISITION OF CONSERVATION IN COMMERCIAL BUILDINGS

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September 1990

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SUMMARY

The quality of indoor air in commercial buildings is dependent on the complex interaction between sources of indoor pollutants, environmental factors within buildings such as temperature and humidity, the removal of air pollutants by air-cleaning devices, and the removal and dilution of pollutants from outside air. To the extent that energy conservation measures (ECMs) may affect a number of these factors, the relationship between ECMs and indoor air quality is difficult to predict. For example, depending on the location of pollutant sources (indoor or outdoor), indoor pollutant concentrations may be either increased or decreased by a reduction in ventilation. For instance, additional caulking and weatherstripping will reduce the infiltration/exfiltration rate. This reduction in ventilation may increase indoor pollutant levels originating from an indoor source because of a reduction in fresh air dilution and removal. On the other hand, the same ECM will decrease the levels for a pollutant with an outdoor source location by reducing the transport of that pollutant to the indoor environment.

Energy conservation measures may affect pollutant levels in other ways. Conservation measures, such as caulking and insulation, may introduce sources of indoor pollutants. Measures that reduce mechanical ventilation may allow pollutants to build up inside structures. Finally, heating, ventilating, and air-conditioning (HVAC) systems may provide surface areas for the growth of biogenic agents, or may encourage the dissemination of pollutants throughout a building.

Conservation measures that involve carefully maintaining and operating mechanical equipment may improve the quality of indoor air. In some instances, proper operation and design will increase ventilation quality and effectiveness and thus improve pollutant removal mechanisms. In addition, inspections and proper installation will make the buildup of biogenic colonies less likely in HVAC systems.

Information about indoor air quality and ventilation in both new and existing commercial buildings is summarized in this report. Sick building syndrome and specific pollutants are discussed, as are broader issues such as ventilation, general mitigation techniques, and the interaction between

energy conservation activities and indoor air quality. Pacific Northwest Laboratory[a] (PNL) prepared this review to aid the Bonneville Power Administration (Bonneville) in its assessment of potential environmental effects resulting from conservation activities in commercial buildings.

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CONTENTS

SUMMARY iii

1.0 INTRODUCTION 1.1

2.0 POLLUTANT CHARACTERIZATION 2.1

2.1 SICK BUILDING SYNDROME AND THE COMBINED EFFECTS OF POLLUTANTS 2.1

2.2 VOLATILE ORGANIC COMPOUNDS 2.5

2.2.1 Volatile Organic Compound Sources 2.6

2.2.2 Volatile Organic Compound Source Strengths 2.8

2.2.3 Commercial Building Volatile Organic Compound Concentrations 2.8

2.2.4 Environmental Factors 2.13

2.2.5 Standards, Guidelines, and Regulatory Effects 2.18

2.2.6 Interaction with Energy Conservation Measures 2.18

2.2.7 Specific Mitigation Techniques 2.22

2.3 RESPIRABLE SUSPENDED PARTICULATES 2.24

2.3.1 Pollutant Sources and Source Strength 2.25

2.3.2 Concentrations in Commercial Buildings 2.27

2.3.3 Environmental Factors 2.28

2.3.4 Standards, Guidelines, and Regulatory Effects 2.28

2.3.5 Interactions with Energy Conservation Measures 2.29

2.3.6 Specific Mitigation Techniques 2.30

2.4 BIOLOGICAL CONTAMINANTS 2.31

2.4.1 Pollutant Sources and Source Strength 2.32

2.4.2 Concentrations in Commercial Buildings 2.33

2.4.3 Environmental Factors 2.34

2.4.4 Standards, Guidelines, and Regulatory Effects 2.34

2.4.5 Interactions with Energy Conservation Measures 2.35
2.4.6 Specific Mitigation Techniques 2.36
2.5 COMBUSTION GASES 2.38
2.5.1 Pollutant Sources and Source Strength 2.38
2.5.2 Concentrations in Commercial Buildings 2.40
2.5.3 Environmental Factors 2.41
2.5.4 Standards, Guidelines, and Regulatory Effects 2.43
2.5.5 Interactions with Energy Conservation Measures 2.43
2.5.6 Mitigation Techniques 2.44
2.6 RADON 2.45
2.6.1 Pollutant Sources and Source Strength 2.45
2.6.2 Concentrations in Commercial Buildings 2.46
2.6.3 Environmental Factors 2.47
2.6.4 Standards, Guidelines, and Regulatory Effects 2.47
2.6.5 Interactions with Energy Conservation Measures 2.48
2.6.6 Specific Mitigation Techniques 2.48
3.0 VENTILATION 3.1
3.1 CHARACTERIZATION OF VENTILATION 3.1
3.1.1 Infiltration and Natural Ventilation 3.1
3.1.2 Mechanical Ventilation 3.2
3.2 INTERACTION WITH POLLUTANTS 3.4
3.3 STANDARDS 3.4
3.4 CHARACTERIZATION OF BUILDING AIR EXCHANGE RATES 3.5
4.0 MITIGATION 4.1
4.1 BUILDING COMMISSIONING 4.1
4.1.1 Costs 4.2

4.1.2 Commercial Availability 4.3

4.2 SOURCE AVOIDANCE AND CONTROL 4.3

4.2.1 Costs 4.4

4.2.2 Commercial Availability 4.4

4.3 INDOOR AIR QUALITY MANAGEMENT 4.4

4.4 BUILDING DIAGNOSTICS 4.5

4.4.1 Costs 4.6

4.4.2 Commercial Availability 4.6

4.5 MECHANICAL CONTROL OF INDOOR AIR POLLUTANTS 4.7

4.5.1 Mechanical Ventilation 4.7

4.5.2 Air Treatment 4.8

5.0 ENERGY CONSERVATION MEASURES AND INDOOR AIR QUALITY - IMPLICATIONS 5.1

6.0 REFERENCES 6.1

FIGURES

2.1 Caulking Compound Emission Factor Versus Time Total Measured Organics 2.16

2.2 Caulk Emissions Versus Time -- Three Compounds 2.17

TABLES

2.1 Examples of Organic Compounds and Sources 2.7

2.2 Summary of Emission Results from Building Materials 2.9

2.3 Summary of Emissions from Energy-Efficient Building Materials 2.10

2.4 Mean Indoor Concentration of Volatile Organic Compounds Found in Public Buildings 2.12

2.5 Mean 3-Day Concentrations of Organics in Three New Buildings 2.14

2.6 Concentrations of Total Volatile Organic Compounds in 15 Buildings 2.15

2.7 Projected Total Organic Concentration Increments in Buildings with Unaged Building Materials 2.15

2.8 World Health Organization Working Group Consensus of Concern About Indoor Air Pollutants at 1984 Levels of Knowledge 2.19

2.9 U.S. Formaldehyde Standards 2.20

2.10 Threshold Limit Values of Some Organics Frequently Encountered in Indoor Air 2.21

2.11 Pollutant Emission Rates 2.25

2.12 Emission Factors for Appliances 2.39

2.13 OSHA Standards for Combustion Gases 2.43

2.14 Radon Action Levels and Guidelines 2.47

3.1 Recommended Airflow Rates Contained in ASHRAE Standard 62-1981 and 62-1989 . . . . . 3.6

3.2 Average Ventilation/Infiltration for Eight Federal Buildings . . 3.7

4.1 Adsorption Capacities of Activated Carbon for 27 Carcinogenic Vapors at 20° 4.12

4.2 Activated Carbon Adsorption Impregnations 4.13

5.1 List of Candidate Energy Conservation Measures and Associated IAQ Impacts 5.3

1.0 INTRODUCTION

The Bonneville Power Administration (Bonneville) has taken a leading role among federal agencies in assessing the environmental impacts of indoor air pollutants and designing appropriate program responses. These efforts have included extensive research programs into residential ventilation and indoor pollution characterization and monitoring. Bonneville has also prepared three environmental documents under the National Environmental Policy Act (NEPA) that focused on indoor air quality issues (Bonneville 1982, 1984, 1988).

One of these documents, the 1982 *Environmental Assessment of Energy Conservation Opportunities in Commercial-Sector Facilities in the Pacific Northwest* (Bonneville 1982), supported conservation programs in existing commercial buildings. Bonneville is now planning the implementation of aggressive commercial conservation acquisition programs in both new and existing buildings. Because of changing information, and because of the change in scope of the programs being designed, Bonneville is now reexamining the potential environmental effects of conservation activities in commercial buildings. Pacific Northwest Laboratory[a] (PNL) prepared this review of information about indoor air quality in commercial buildings to aid Bonneville in its assessment of potential environmental effects.

This report summarizes information about indoor air quality and ventilation in both new and existing commercial buildings. The quality of indoor air is dependent on the complex interaction between sources of indoor pollutants, environmental factors within buildings such as temperature and humidity, the removal of air pollutants by air cleaning devices, and the removal and dilution of pollutants from inside air by ventilation. This report addresses these issues for specific pollutants in Section 2, and more generally in Sections 3 and 4. Section 5 focuses on linking indoor air quality issues with specific conservation measures.

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2.0 POLLUTANT CHARACTERIZATION

The dynamics of specific types of pollutants in the commercial building environment are reviewed in this section. Specific pollutant types include volatile organic compounds (VOC), respirable suspended particulates (RSP), biological contaminants, combustion gases, and radon. Before discussing pollutants individually, Section 2.1 addresses the characteristics of pollutants and the sick building syndrome.

2.1 SICK BUILDING SYNDROME AND THE COMBINED EFFECTS OF POLLUTANTS

One national survey reports that 25% of American workers feel that the quality of their workplace air affects their work adversely (Sheldon et al. 1988a). Woods (as reported in Levin 1989a) found that 20% of the office workers in the United States may be affected by sick building syndrome (SBS). Sick building syndrome refers to health and comfort problems associated with working or being in a particular building (EPA 1988). The term generally applies to problems related to indoor air pollution, rather than describing complaints stemming solely from humidity control or inadequate temperature. If the problems result in clinically defined illness, disease, or infirmity in occupants, the building is said to manifest building-related illness (EPA 1988). These conditions may be caused by a number of interacting factors. The Environmental Protection Agency (EPA) lists the following key contributing factors:

- inadequate ventilation
- pollutants emitted inside of buildings
- contamination from outside sources
- biological contamination.

These factors interact with other environmental considerations such as inadequate temperature, uncomfortable humidity, or poor lighting. The causes of SBS and building-related illness are complex. Once a building has been implicated, the causes often remain undetermined. Perhaps the best explanation for occupant responses in the absence of standardized testing and pollutant concentration requirements was offered by Carey et al. (1985):

"Virtually all cases of sick building syndrome are discovered by nature's imperfect pollution detector, the human body."

Molhave (as reported in Levin 1989a) reports the following common symptoms reported in cases of SBS:

- sensoric irritation in eye, nose or throat, such as dryness, stinging, smarting, irritating sensation, hoarseness, and changed voice
- skin irritation, such as reddening of skin, stinging, smarting, itching sensation, dry skin
- neurotoxic symptoms such as mental fatigue, reduced memory, lethargy, drowsiness, reduced power of concentration, reduced memory, headache, dizziness, intoxication, nausea, tiredness
- unspecified hyperreactions, such as running nose and eyes, asthma-like symptoms, respiratory sounds
- odor and taste complaints, such as changed sensitivity and unpleasant odor or taste.

Molhave (1990) further suggests that human response may be related to a biological model consisting of three stages:

- sensory perception of the environment - The senses include odor, taste, and chemical sense. Chemical sense refers to nerves in the mucousal membranes and skin that react to chemical stimuli. Activation of the senses leads to irritation and possibly a protective response, such as sneezing.
- weak inflammatory reactions - Inflammatory reactions are related to microbiologic, metabolic, or immune system reactions and are generally considered to be a protective reaction to potential cell damage. Acute, reversible reactions seem to be relevant to low-level pollutant exposure in nonindustrial environments.
- environmental stress reactions - The constant effort needed to identify wanted and to override unwanted sensory information, and the efforts needed to maintain protective reflexes may cause secondary effects, such as headache.

Key pollutants that may be associated with SBS are discussed in Sections 2.2 through 2.6. Although it is not the source of the pollutants causing distress, inadequate ventilation is an often-cited cause of sick buildings (Burge 1990). As of December 1985, the National Institute for Occupational

Safety and Health (NIOSH) had conducted 365 health-hazard evaluations of building-related problems. The NIOSH has concluded in most cases that the problem could be eliminated by improved ventilation (Melius et al. 1984).

Burge (1990) states that researchers consistently link an increased number of symptomatic building occupants with microbiological contamination either from dampness or from chillers and humidifiers. However, when airborne levels of bacteria and fungi are measured, no direct relationship has been found with SBS symptoms and airborne levels. It is likely that the problems relate to mycotoxins and endotoxins, which microbiological organisms release. There is also increasing evidence that biocides, such as isothialzolones, glutaraldehyde, and chlorhexidine in low concentrations may cause symptoms of SBS.

Recently Molhave (1990) has postulated that total volatile organic compounds (TVOC) can be used to define a concentration level at which SBS symptoms begin. The no effect level seems to be at 0.16 mg/m^3. An exposure range of from 0.2 to 3 mg/m^3 may result in possible health effects. At concentrations greater than 3 mg/m^3, discomfort is expected; at concentrations greater than 25 mg/m^3, toxic effects may appear. However, the TVOC must be grouped using common characteristics. At present there is little agreement on how these groupings should be established. Siefert (1990) points out that until conventions are established for these groupings, it will be difficult to promulgate regulations or guidelines.

Principles for a future ventilation standard that acknowledges all pollution sources have been proposed by Fanger (1990, 1989). Required ventilation levels would be calculated based on the total indoor pollution load, the available outdoor air quality, and the desired level of indoor air quality. In this standard two new units would be utilized, the olf and decipol. Perceived air quality is expressed in decipol. One decipol is the perceived air quality in a space with a pollution strength of one olf, ventilated by 10 l/s of clean air (1 decipol - 0.1 olf/[l/s]). One olf is defined as the pollution from a standard person. However, any pollution source can be expressed in olfs. The conversion would be the number of standard persons required to make the air as annoying as the actual pollution

source. Panels of judges would make subjective measurements of the level of annoyance. Thus, given a certain percentage of dissatisfied among a panel of judges, the number of standard persons (olfs) that would cause the same dissatisfaction could be calculated. The olf value is not related to possible health risks of pollutants.

Other investigations have also found a correlation between SBS and ventilation conditions. Levin (1989a) reports that four British studies found higher symptom prevalence rates in sealed, mechanically ventilated buildings than in those naturally ventilated. One of these studies found that buildings with humidification had the greatest symptom rates. A third study found a threefold excess of symptom rates in mechanically ventilated buildings compared to naturally ventilated buildings. A study of 30 British buildings found little difference between natural and mechanically ventilated buildings, but did find higher symptom prevalence in air-conditioned buildings as compared to non-air-conditioned buildings. This study also found higher symptom rates in women than in men, and in public-sector buildings than in private-sector buildings.

In contrast to these studies finding ventilation to be a significant causal factor, several investigators have suggested that multiple factors contribute to SBS, none of which alone would result in complaints and symptoms (Levin 1989a). A comprehensive study known as the Danish Town Hall Study investigated 27 buildings and found that differences in the prevalence of symptoms among buildings was significant and was correlated with building characteristics and occupant factors. Building and occupational factors that explained differences in symptom prevalence included the following:

- Age of the building, wherein the lowest prevalence of symptoms was found in the oldest buildings. Symptoms varied greatly by building, suggesting that the symptoms were building-related.

- Elevated rates of mucosal irritation were associated with the total weight and potentially allergenic fraction of floor dust, the presence of open shelves, the area of fleecy material, the number of work stations, and air temperature.

- Symptoms correlated strongly with job category, with the highest prevalence of symptoms found in subordinate job positions. Photo-printing, working at video display terminals, and handling carbon-less paper was related to both mucosal and general symptoms.

- Women had a higher symptom rate than men and complained more frequently about indoor climate. The number of weekly working hours of women weakly corresponded with reports of mucosal and general symptoms.

Lighting can also affect occupants' perceptions of buildings. Sterling and Sterling (1984) report that there is a significant relationship between poor lighting and reported building illness. Office workers having poor building lighting were found to be more likely to think of their buildings as contributing to poor health. Noise has also been identified as a potential cause of SBS symptoms.

The importance of indoor air quality is being recognized with an increase in legislative attention. In the spring of 1989, the Indoor Air Quality Act of 1989 (H.R. 1530 and S. 657) was introduced in both houses of the U.S. Congress. Though the bill has yet to be passed, it has 47 current cosponsors in the House and 19 cosponsors in the Senate.[a] The bill directs the Administrator of the EPA to develop a national research, development, and demonstration program. This program would focus on human health effects and the idertification of types and levels of contaminants. Other features would include the funding of demonstration projects, the formation of a national clearinghouse, and the establishment of advisory pollutant levels.

2.2 VOLATILE ORGANIC COMPOUNDS

Volatile organic compounds refers to a class of carbon-based chemicals that evaporate easily at room temperature and thus give off vapors that can be inhaled.

(a) Personal communication with Gordon J. Evans, District Assistant to Congressman Ron Wyden. 10 August 1990.

2.2.1 Volatile Organic Compound Sources

The explosion of new building materials, consumer goods, and office equipment developed since World War II has made VOC sources ubiquitous. Wallace (1987) has concluded that nearly every home and place of business contains common materials that may cause elevated levels of chemical exposure. Over 900 separate volatile compounds have been found in indoor air. Organic compounds can be grouped according to structural similarities. Examples of organic compound types and their sources are shown in Table 2.1.

Wallace identified from 10 to 82 vapor compounds (stainless steel polish had the most) in chamber study experiments. The study and experiments assessed 15 materials grouped in the four categories of cleaners and polishes, floor and wall coverings, glues, and pesticides.

In other chamber studies, the National Aeronautics and Space Administration (NASA) has tested over 5000 materials that may find their way onto space craft. Ozkaynak (1987) has divided these materials into groupings such as adhesives, coatings, fabric, foam, labels, lubricant, papers, plastic, rubber, tape, thread, velcro, wire, clothing, computer equipment, cosmetics, deodorants, electrical equipment, and so on. Ozkaynak reported findings for 19 VOCs. Of these, benzene was found in 387 materials, styrene in 284, trichlorethylene in 381, and ethyl benzene in 19. The highest concentrations were found in health and beauty aids. Mass balance calculations of indoor pollutant concentrations have also shown paint to be a substantial source (Baechler et al. 1989).

Sheldon et al. (1988b) found that building materials collected from new buildings emitted high rates of the compounds found in the buildings. Further, these compounds were similar in two new buildings, suggesting that the findings may be generally true for many buildings. Materials emitting these compounds at the highest rates were surface coatings such as adhesives, caulking, and paints; wall and floor coverings such as molding, linoleum tile, and carpet; and other materials such as telephone cable.

TABLE 2.1. Examples of Organic Compounds and Sources

Pollutant Type	Organic Compounds	Indoor Sources
Aliphatic and oxygenated aliphatic hydrocarbons	α-pinene, n-decane, n-undecane, n-dodecane, propane, butane, n-butylacetate, ethoxy ethyl acetate octane	Cooking and heating fuels, aerosols propellants, cleaning compounds, paints, carpet, moldings, particle board, refrigerants, lubricants, flavoring agents, perfume base
Halogenated hydrocarbons	Chloroform, methyl chloroform, dichloromethane, polychlorinated biphenyls, 1,1,1-trichloroethane, trichloroethylene tetrachloroethylene chlorobenzene, dichlorobenzene carbon tetrachloride	Aerosol propellants, fumigants, pesticides, refrigerants, adhesives, caulk, paint, linoleum tile, carpet, latex paint, and degreasing, dewaxing, and dry cleaning solvents
Aromatic hydrocarbons	Xylene, ethyl benzene, trimethylbenzene, ethyltoluene, propylbenzene, benzene, styrene, toluene	Paints, varnishes, glues, enamels, lacquers, cleaners, adhesives, molding, insulation, linoleum tile, carpet
Alcohols	Ethanol, methanol	Lacquers, varnishes, polish removers, adhesives
Ketones	Acetone, diethyl ketone, methyl ethyl ketone	Lacquers, varnishes, polish removers, adhesives, cleaners
Aldehydes	Formaldehyde, nonanal	Fungicides, germicides, disinfectants, artificial and permanent-press textiles, paper, particle boards, cosmetics, flavoring agents

2.2.2 Volatile Organic Compound Source Strengths

Emission rates from 31 materials collected from new office buildings are shown in Table 2.2. The results show that while some solvent-based materials were the highest emitters, other solvent-based building materials emitted none of the target compounds (Sheldon et al. 1988b).

Building materials, such as caulk and insulation, associated with energy-efficiency measures have been found to emit VOCs. Table 2.3 summarizes emissions from the materials that have been tested in chamber studies. These emissions and their rates can be compared with those listed in Table 2.2. An environmental assessment (EA) prepared for the U.S. Department of Energy (DOE) (1986) concluded that emissions from five insulation types did not contribute significantly to indoor VOC concentrations. This conclusion was based on mass-balance calculations using emission rates from chamber study tests of building materials. Table 2.3 summarizes chamber studies of building materials associated with energy-efficient construction and covers a broader range of materials than those included in the EA.

2.2.3 Commercial Building Volatile Organic Compound Concentrations

The levels of individual VOCs found in buildings are often several times below threshold limit values (TLVs) for occupational settings, or levels considered to be harmful for any one chemical in an occupational setting. However, many indoor VOC concentrations have been found to be much higher than levels found outdoors. Sheldon et al. (1988a) found indoor-outdoor ratios of total organics of 2 or 3 to 1 in three older buildings. In a new office building, this ratio was 50:1, dropping to 10:1 after two months, and 5:1 after three additional months. A total of about 500 compounds were found at least once from all of the buildings sampled.

In a companion study, Sheldon et al. (1988b) found indoor levels of total organics in two new buildings up to 400 times greater than outdoor concentrations. After several months these concentrations dropped to 3 to 30 times outdoor levels. Table 2.4 gives a comparison of mean VOC concentrations

TABLE 2.2. Summary of Emission Results from Building Materials[a]

Sample	Emission Rate, $\mu g/m^2/h$			
	Aliphatic and Oxygenated Aliphatic Hydrocarbons	Aromatic Hydrocarbons	Halogenated Hydrocarbons	All Target Compounds
Cove adhesive	(b)	(b)	(b)	>5000
Latex caulk	252	380	5.2	637
Latex paint A	111	52	86	249
Carpet adhesive	136	98	(c)	234
Black rubber molding	24	78	0.88	103
Small-diameter telephone cable	33	26	1.4	60
Vinyl cove molding	31	14	0.62	46
Linoleum tile	6.0	35	4.0	45
Large-diameter telephone cable	14	20	4.3	38
Carpet	27	9.4	---	36
Vinyl edge molding	18	12	0.41	30
Particle board	27	1.1	0.14	28
Polystyrene foam insulation	0.19	20	1.4	22
Tar paper	3.2	3.1	---	6.3
Primer/adhesive	3.6	2.5	---	6.1
Latex paint B	---	3.2	---	3.2
Water repellent mineral board	1.1	0.43	---	1.5
Cement block	---	0.39	0.15	0.54
Polyvinyl chloride pipe	---	0.53	---	0.53
Duct insulation	0.13	0.15	---	0.28
Treated metal roofing	---	0.19	0.06	0.25
Urethane sealant	---	0.13	---	0.13
Fiberglass insulation	---	0.08	---	0.80
Exterior mineral board	---	0.03	---	0.03

(a) Source: Adapted from Sheldon et al. (1988b).
(b) Emission rate for cove adhesive is a minimum value; sample was overloaded. It is estimated that cove adhesive is one of the highest emitters of volatile organics.
(c) No detectable emissions.

TABLE 2.3. Summary of Emissions from Energy-Efficient Building Materials

Investigator	Technique	Source	Emissions	Concentration or Emissions Rate
Miele 1989	Large scale test chamber	R-30 bonded	Formaldehyde--this was the only compound measured--reported values are chamber concentrations.	0.065 ppm @ 77°F[a]
		Fiberglass insulation Kraft-faced		0.072 ppm @ 77°F
		R-19 Kraft-faced		0.072 ppm @ 77°F
		R-11 Kraft-faced		0.072 ppm @ 77°F
		R-11 unfaced		0.085 ppm @ 77°F
		R-13 unfaced		0.085 ppm @ 77°F
		Duct Line--non-woven fabric facing		0.015 ppm @ 77°F[b]
		Duct Line--non-woven fabric facing		0.020 ppm @ 110°F[b]
		Duct Board--1" foil scrim Kraft facing		0.028 ppm @ 77°F[b]
		Duct Board--1" foil scrim Kraft facing		0.051 ppm @ 110°F
		Duct Board--1" foil scrim Kraft facing		0.070 ppm @ 110°F
Tichenor and Mason 1988	Test chamber	Silicone caulk	Total organics--major compounds identified include: methyl ethyl ketone, butyl propionate, 2-butoxyethanol, butanol, benzene, and toluene.	
			Sample age: 0.5 hr	50.0 mg/m^2-h
			Sample age: 1.0 hr	30.0 mg/m^2-h
			Sample age: 5.0 hr	2.0 mg/m^2-h
White, Reavess, Fleist, and Mann 1988	Review of test chamber data	Caulking compound	C-10 alkene	1.23 mg/m^2-h
			C 4-alcohol	<0.01 mg/m^2-h
			N-decane	6.82 mg/m^2-h
			N-undecane	<0.01 mg/m^2-h
			Toluene	0.02 mg/m^2-h
			Ethyl benzene	7.32 mg/m^2-h
			2-xylene	1.02 mg/m^2-h
			3-xylene	2.77 mg/m^2-h
			4-xylene	24.20 mg/m^2-h
		Insulation foam	VOC	2.3 mg/m^2-h

TABLE 2.3. (contd)

Investigator	Technique	Source	Emissions	Concentration or Emissions Rate
van der Wal, Mouns, and Steelage 1987	Test chamber	Rock wool and glass fibers. The following compounds were found in at least one sample of either insulation type taken from a home, school, or office.	18 aldehydes and ketones	Not qualified--concentration greatest when samples were wet.
Sheldon, Thomas and Jungers 1986	Test chamber	Fiberglass insulation	Aromatic hydrocarbons	0.00008 mg/m^2-h
		Polystyrene foam and insulation	Aromatic hydrocarbons	0.020 mg/m^2-h
			Halogenated organics	0.00134 mg/m^2-h
			Volatile aromatic compounds	0.02017 mg/m^2-h
			Aliphatic and oxygenated aliphatic compounds	0.00019 mg/m^2-h
			Z-butene-1-01, Dentane, 1,2-dimethyl-cyclopropane, benzonitrile, benzaldehyde	Not quantified
		Duct insulation	Aromatic hydrocarbons	0.00015 mg/m^2-h
			Aliphatic and oxygenated aliphatic organics	0.00013 mg/m^2-h
			Trimethylhexene	Not quantified
		Latex caulk	Halogenated organics	0.005[c] mg/m^2-h
			Volatile aromatic compounds	0.3809[c] mg/m^2-h
			Aliphatic and oxygenated aliphatic organics	0.251[c] mg/m^2-h
			Aciphatic hydrocarbons, aromatic hydrocarbons	Not quantified
Molhave 1982	Test chamber	Silicone caulk	23 compounds	26.0 mg/m^2-h
		Mineral wool	13 compounds	0.012 mg/m^2-h
		Polystyrene foam insulation	15 compounds	1.4 mg/m^2-h
		Polyurethane foam insulation	5 compounds	0.12 mg/m^2-h
Miksch, Hollowell, and Schmidt 1982	Test chamber	Phenoseal Brand caulk[d]	Butylacetate, 2-ethanol	Not quantified
		Vinyl acrylic latex caulk[d]	Ethylene glycol	Not quantified
		Butyl caulk[d]	Octane, octene, nonane, aliphatic hydrocarbons, alkylbenzenes	Not quantified

(a) Chamber background formaldehyde levels ranged from 0.024 ppm to 0.028 ppm.
(b) Formaldehyde concentration after test was less than background level, suggesting test material was a sink.
(c) Minimum value, compound saturated the detector during analysis.
(d) Sample aged 24 hours before vapor collected.

TABLE 2.4. Mean Indoor Concentration of Volatile Organic Compounds Found in Public Buildings

Compounds	Mean Indoor Concentration (mg/l)									
	Martinsburg, WV			Fairfax, VA		Worcester, MA		Washington, D.C.	Cambridge, MA	Martinsburg, WV
	Hospital (New)[a]			Office (New)[b]		Nursing Home (New)[c]		Office (Old)	Office/School (Old)	Nursing Home (Old)
	Trip 1 (7/84)	Trip 2 (10/84)	Trip 3 (8/85)	Trip 1 (1/85)	Trip 2 (4/85)	Trip 1 (4/85)	Trip 2 (8/85)	Trip 1 (8/84)	Trip 1 (2/85)	Trip 1 (7/84)
Aromatic Hydrocarbons										
Benzene	1.55	2.13	2.88	2.74	4.95	1.70	2.44	5.61	4.50	3.13
m-Xylene	6.88	3.13	9.91	41.53	15.05	23.80	5.33	27.11	8.72	2.95
o-Xylene	3.05	0.91	3.07	18.40	3.67	8.92	2.07	9.28	3.43	0.99
Styrene	1.00	1.07	1.33	2.52	2.87	2.99	1.27	2.36	1.32	1.19
Ethylbenzene	1.94	1.01	2.88	51.26	5.37	7.90	2.15	10.15	2.69	0.97
Isopropylbenzene	0.31	ND[d]	0.33	3.94	0.67	2.27	0.33	0.79	0.36	ND
n-propylbenzene	ND	ND	ND	5.00	1.13	2.99	0.70	1.22	0.56	ND
m-Ethyltoluene	1.11	0.86	1.48	27.41	5.57	12.38	2.62	6.07	2.62	0.90
o-Ethyltoluene	ND	ND	0.66	8.89	2.08	4.01	0.73	1.60	0.74	ND
1,2,3-Trimethylbenzene	0.63	0.43	0.76	15.10	2.91	5.32	0.72	1.80	1.06	0.79
1,2,4-Trimethlybenzene	1.48	0.98	1.82	73.51	7.27	13.95	2.52	6.28	2.80	0.98
1,2,5-Trimethylbenzene	ND	ND	0.75	16.97	2.75	6.83	0.92	1.83	1.14	ND
Aliphatic Hydrocarbons										
a-Pinene	ND	ND	ND	14.13	24.64	5.19	ND	ND	2.65	ND
n-Decane	3.65	2.73	2.71	436.38	15.24	68.27	3.81	2.26	5.98	1.87
n-Undecane	3.31	1.96	2.34	210.80	33.93	68.51	3.48	2.85	6.77	ND
n-Dodecane	ND	ND	ND	152.69	23.74	31.42	ND	ND	2.23	ND
Chlorinated Hydrocarbons										
1,2-Dichloroethane	2.06	1.49	2.21	ND	4.51	ND	ND	ND	ND	ND
1,1,1,-Trichloroethane	4.98	4.50	15.54	12.54	38.85	4.03	1.76	40.98	10.69	3.09
Trichloroethylene	1.05	ND	ND	ND	7.93	2.58	0.57	0.61	10.89	ND
Tetrachloroethylene	ND	ND	1.79	ND	1.64	1.13	0.96	3.97	4.11	0.99
p-Dichlorobenzene	ND	ND	6.61	ND	2.64	2.17	0.62	0.60	ND	ND
Oxygenated Hydrocarbons										
n-Butylacetate	ND	ND	ND	ND	6.34	ND	1.22	2.63	1.48	ND
2-Ethoxyethyl acetate	1.31	ND	ND	ND	2.16	9.58	ND	1.67	ND	ND

(a) Building completed ~34 weeks before first monitoring trip.
(b) Building completed ~1 week before first monitoring trip.
(c) Building completed ~4 weeks before first monitoring trip.
(d) Below the quantifiable limit.
Source adapted from Shelton et. al. 1988b

found in a variety of building types, from a paper by Jungers and Sheldon (1987). VOC concentrations in three new buildings measured soon after construction and after occupancy are shown in Table 2.5 (Wallace et al. 1987).

In 109 total VOC samples taken from 15 office buildings where occupants reported widespread occurrence of annoyance and discomfort on at least one floor or zone, Morey and Jenkins (1989) found that 20% of the samples exceeded or were equal to 1000 $\mu g/m^3$. And 6% of the buildings had concentrations equal to or exceeding 2000 $\mu g/m^3$. Table 2.6 shows concentrations of total VOCs from the 15 buildings.

In a study of 38 commercial buildings in the Pacific Northwest, Turk et al. (1987) found low formaldehyde concentrations. The average levels in 21 of the buildings were above the 20-parts per billion (ppb) detection limit. None of the buildings had whole-building mean levels exceeding the 1981 ASHRAE guideline of 100 ppb. Three buildings had comparatively elevated levels. The researchers suggest that the elevated levels in one building were caused by formaldehyde-bonded products used in new construction and, in another building, similar products used in remodeling. The likely source in a third building was a print shop that shared the same structure.

Table 2.7 is adapted from the 1986 U.S. Department of Energy EA and shows calculated organic concentrations for commercial buildings in Seattle.

For comparison, Molhave (1985) has suggested that people begin sensing total VOCs in indoor air at about 1000 $\mu g/m^3$. Molhave's work also suggests that SBS may result from the additive or synergistic effect of the complex mixture of VOCs found in buildings, rather than from any single pollutant (Molhave 1985; Molhave et al. 1985). His work may be among the first objective proof that a major component of the SBS may be common indoor organic vapors at levels far below occupational health standards (Wallace 1985).

2.2.4 Environmental Factors

Organic vapors are released to indoor air from a multitude of products, cleaning agents, and building materials. The factors affecting the release and interaction of these vapors are complex and include temperature, humidity,

TABLE 2.5. Mean 3-Day Concentrations ($\mu g/m^3$) of Organics in Three New Buildings

	Recently Constructed			Following Occupancy				
	Office 1	Office 2	Nursing Home	Office 1	Office 2	Office 1	Nursing Home	Maximum Outdoor Concentration
Number of Samples	20	18	18	19	18	20	18	6
Time Since Completion (Weeks)	1	2	6	7	15	22	23	--
Aliphatics								
α-Pinene	NM[a]	14	5	NM	25	NM	ND[b]	ND
Decane	380	440	68	38	15	4	4	4
Undecane	170	210	69	48	34	13	4	2
Dodecane	47	150	31	19	24	5	NO	1
Aromatics								
Benzene	5	3	2	7	5	7	2	5
Xylenes	214	59	33	27	19	12	7	6
Styrene	8	3	3	7	3	4	1	4
Ethylbenzene	84	51	8	6	5	5	2	2
Propylbenzenes	NM	9	5	NM	2	NM	1	ND
Ethyltoluenes	NM	36	16	NM	8	NM	3	2
Trimethylbenzenes	NM	110	26	NM	13	NM	4	3
Chlorinated								
1,2-Dichloroethane	NM	ND	ND	NM	5	NM	ND	ND
1,1,1,-Trichloroethane	380	13	4	100	39	49	2	10
Trichloroethylene	1	ND	3	38	8	27	1	1
Tetrachloroethylene	7	ND	1	2	2	3	1	1
Dichlorobenzenes	1	ND	2	1	3	1	1	ND
Chloroform	1	NM	NM	2	NM	18	NM	17
Carbon tetrachloride	1	NM	NM	1	NM	1	NM	1
1,2-Dichloroethane	NM	ND	ND	NM	5	NM	ND	ND

(a) Not measured.
(b) Not detected.
Source is adapted from Wallace et al 1987

TABLE 2.6. Concentrations of Total Volatile Organic Compounds in 15 Buildings

Location	Concentration of TVOC in $\mu g/m^3$	Number Samples	Percent of Total Samples
Indoors	=> 2000	6	6
Indoors	=> 1000 to 1999	15	14
Indoors	=> 500 to 999	25	23
Indoors	=> 200 to 499	31	28
Indoors	=> 100 to 199	19	17
Indoors	=> 1 to 99	13	12
Outdoors	=> 500 to 999	3	13
Outdoors	=> 200 to 499	5	22
Outdoors	=> 100 to 199	7	30
Outdoors	=> 1 to 99	8	35

Average of 109 indoor samples = 660 $\mu g/m^3$
Average of 23 outdoor samples = 232 $\mu g/m^3$
Source: Adapted from Morey and Jenkins 1989

TABLE 2.7. Projected Total Organic Concentration Increments in Buildings with Unaged Building Materials (mg/m^3)

Building Category	ASHRAE Standard 90A-1980 Design	Proposed Standard Design	Increment
Small Office	0.082	0.594	0.511
Medium Office	0.240	0.432	0.191
Large Office	1.005	0.006	-0.999
Retail Store	0.013	0.199	0.185
Strip Store	0.002	0.003	0.002
Apartment	0.315	0.792	0.478
Hotel	0.031	0.043	0.013
Warehouse	1.217	16.194	14.976
Assembly	0.001	0.010	0.009
School	0.020	0.024	0.004

time, ventilation, source quantity, the volume of the affected space, the age of the material, and the tendency of walls and other surfaces to absorb and re-emit the pollutant.

Perhaps the best studied of the organics is formaldehyde. Hawthorne and Mathews (1985) have developed models of formaldehyde emissions from pressed wood products using urea-formaldehyde-based glue. These models show that

emission rates increase when air exchange rates increase, product loads decrease, or concentrations decrease. Researchers have also demonstrated that formaldehyde emissions tend to increase as humidity or temperature levels increase. Hawthorne and Mathews (1985) suggest that the expected length of time for a given source of formaldehyde to release about half of its emissions (half-life) may be on the order of a few years. Spengler and Sexton (1983) report a half-life of 4.4 years.

As described earlier in this section, organic emissions testing has been done on materials other than formaldehyde. However, it is difficult to evaluate the limited data on organic emissions because standard testing protocols have not been developed (Tichenor and Mason 1988; Baechler et al. 1989).

For wet materials such as caulk, Tichenor and Mason (1988) have concluded that time, or the age of the sample, is a critical parameter; source durations can be as short as a few hours. Figure 2.1 shows the emission factor of total measured organics from silicone caulk over time at two air exchange rates. Emission rates decrease rapidly with time as the VOCs are depleted from the source. The emission rates are initially higher with the

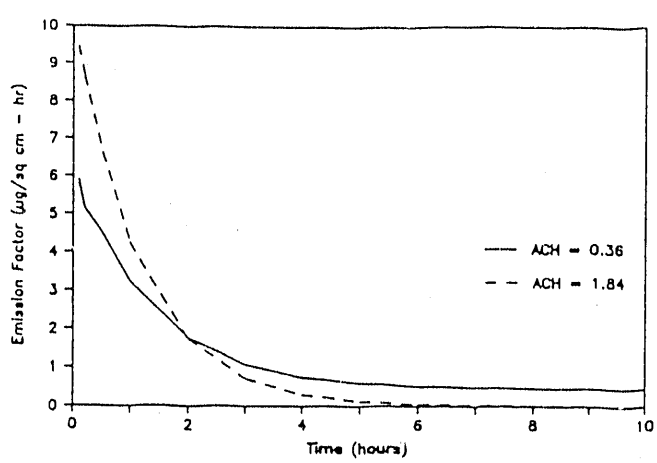

FIGURE 2.1. Caulking Compound Emission Factor Versus Time Total Measured Organics

high air exchange rate, but after 2 hours the emission rates are higher for the low air exchange rate. The high air exchange rate caused the VOCs to be emitted more quickly.

Time can also play an important role in VOC sources that are not wet. As discussed in Section 2.2.2, Sheldon et al. (1988a, 1988b) found substantial reductions in indoor VOC concentrations as a building ages. According to Sheldon et al. (1988a), the half-lives of the compounds found in two new office buildings ranged from 2 to 8 weeks. Thus, based on this limited data, Sheldon concludes that the time for the building to approach outdoor VOC concentrations would range from 3 to 12 months. As time passes, the original source may be depleted. But sinks--sources that adsorb the pollutant--can re-emit the pollutant to the air (Tichenor et al. 1990; Berglund, et al. 1988). Modeling demonstrates that fast-emitting sources could be depleted within 2 days, but re-emission from sinks can affect indoor concentrations for up to 2 weeks (Tichenor et al. 1990).

Tichenor and Mason (1988) also found that a mixture of organic compounds may be emitted from a single source at different rates. Figure 2.2 shows emission factors over time for three of the compounds emitted from silicone caulk. The emission rates vary at any given point in time and decrease at different rates.

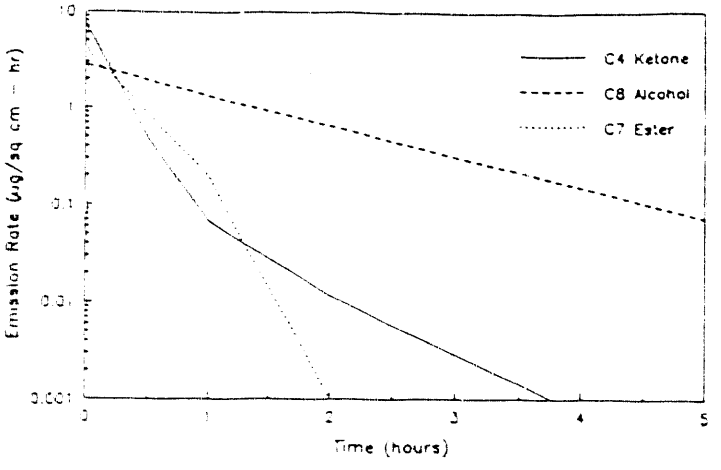

FIGURE 2.2. Caulk Emissions Versus Time -- Three Compounds. T = 23°C; RH = 50%, ach = 1.84

2.2.5 Standards, Guidelines, and Regulatory Effects

Indoor air quality typically is not regulated in nonoccupational settings. Table 2.8 lists the consensus findings of a World Health Organization (WHO) working group on indoor pollutant concentrations. Table 2.9 shows U.S. standards and guidelines for formaldehyde. And Table 2.10 shows occupational threshold limit values (TLVs) and short-term exposure limits (STELs) for a small sample of organics commonly found in indoor air.

Product standards provide one means of limiting the use of high polluting sources. An example of this type of measure is the formaldehyde product standard that Bonneville now enforces in the residential new homes programs. The standard requires that structural building materials used in Bonneville's new homes programs meet the U.S. Department of Housing and Urban Development's (HUD) requirements for manufactured housing, or be rated for exterior use. This product standard helps to reduce formaldehyde emissions from products using urea-formaldehyde-based glues.

Possible means of regulating VOCs are also discussed in Section 2.1.

2.2.6 Interaction with Energy Conservation Measures

Energy conservation measures may affect VOC concentration in one of two ways: by introducing a source of pollutants, or by changing the rate at which pollutants are removed from the indoor space. Potential sources of indoor VOCs from energy conservation measures include caulking compounds and insulation. These materials are discussed in Sections 2.2.1 and 2.2.4. Of the two potential sources discussed, caulking emits the highest rates of VOCs but these are likely to be quickly dissipated. Insulation materials emit pollutants at a lower rate, but have the potential of emitting them over a longer period of time. Emissions from fibrous insulation may be related to how moist the material is (van der Wal 1987).

The second way that energy conservation measures may affect indoor VOC levels is by changing the rate at which pollutants are removed from a space. The most common removal mechanism involves the exchange of indoor and outdoor air in ventilation systems. If conservation measures involve reducing the quantities of outside air without including air cleaning equipment, indoor

TABLE 2.8. World Health Organization Working Group Consensus of Concern About Indoor Air Pollutants at 1984 Levels of Knowledge

Pollutant[a]	Concentrations[b] Reported	Concentrations[b] of Limited or No Concern	Concentration[b] of Concern	Remarks
Tobacco smoke (passive smoking)				
Respirable particulates	0.05-0.7	<0.1	>0.15	Japanese standard 0.15 mg/m^3
CO	1-1.5	<2	>5	indicator for eye irritation (only from passive smoking)
Nitros-dimethylamine	$(1-50) \times 10^{-6}$	---	---	Mutagens under investigation for carcinogenicity
NO_2	0.05-1	<0.19	>0.32	
CO^2		2% carbon monoxy hemoglobin (COHb)	3% COHb	99.9%[c]
		1-100	<11	>30 Continuous exposure
Radon and Progenys	10-3000 Bq/M^3	-0	70 Bq/m^3	Swedish standard for new houses
Formaldehyde	0.05-2	<0.06	>0.12	Long- and short-term
SO_2	0.02-1	<0.5	>1.35	SO_2 alone short-term
CO_2	600-9000	<1800	>12000	Japanese standard 1800 mg/m^3
O_3	0.04-0.4	0.05	0.08	
Asbestos	<10 $fibres/m^3$	-0	10^5 $fibre/m^3$	For long-term exposure
Mineral fibres	<10 $fibres/m^3$	---	---	Skin irritation
Organics				
Methylene chloride	0.005-1	---	350	TLV[d]
			260	NIOSH[e] recommendations
Trichlormethene	0.0001-0.02	---	270	TLV
			135	NIOSH recommendations
Tetrachloroethene	0.002-0.05	---	335	TLV
1.4 Dichlorobenzene	0.005-0.1	---	450	TLV
Benzene	0.01-0.04	carcinogen	carcinogen	
Toluene	0.015-0.07	---	375	TLV
m.p.-Xylene	0.01-0.05	---	435	TLV
n-Nonane	0.001-0.03	---	1050	ILO[f] (1980)
n-Decane	0.002-0.04	---	---	
Limonene	0.01-0.1	---	560	TLV for turpentine

(a) All gases were considered on their own without other contaminants.
(b) Typical ranges of concentration given in mg/m^3 unless otherwise indicated and for short-term exposures.
(c) According to Environmental Health Criteria No. 4, Geneva World Health Organization, 1977.
(d) TLV (threshold limit values) established by the American Conference of Governmental Industrial Hygienists (1983-1984). The values are for occupation exposures and should be considered as extreme upper limits for nonoccupational population for very short-term exposures.
(e) National Institute for Occupational Safety and Health (NIOSH), USA.
(f) International Labor Organization (ILO).
--- = no meaningful numbers can be given because of insufficient knowledge.

TABLE 2.9. U.S. Formaldehyde Standards

Pollutant	Indoor Standards	Industrial Workplace Outdoor Standards	Standards
Formaldehyde	Federal: 0.4 ppm target ambient level, HUD standard for manufactured homes, achieved through product emission standards of 0.2 and 0.3 ppm[a] (HUD, 24 CFR 3280.308, 1984) (C-14) State: 0.4 ppm standard for indoor exposure (MN statute 144.495, 1985) (C-15)	No federal standard State air quality limits: CT 12.00 $\mu g/m^3$ 8 hr IL 0.0150 $\mu g/m^3$ 1 yr IN 18.000 $\mu g/m^3$ 8 hr MA 0.2000 $\mu g/m^3$ 24 hr NC 300.00 $\mu g/m^3$ 15 min NV 0.0710 $\mu g/m^3$ 8 hr NY 2.0000 $\mu g/m^3$ 1 yr VA 12,999 μgm^3 24 hr (C-8)	OSHA issued a final rule Dec. 4, 1987 (52 FR 46168) lowering a previous standard to the above levels, which was effective on Feb. 2, 1987. Mine Safety and Health Admins. used ACGIH TLVs (C-13)

(a) Emissions must not produce concentrations greater than these. These concentrations are measured using chamber studies.

TABLE 2.10. Threshold Limit Values of Some Organics Frequently Encountered in Indoor Air[a]

Chemical	TLV-TWA mg/m^3	TLV-TWA ppm	TLV-STEL mg/m^3	TLV-STEL ppm	Source
Acetone	1780	(750)	2375	(1000)	Lacquer solvent
Ammonia	18	(25)	27	(35)	Cleaner
Benzene	30	(10)	75	(25)	Adhesive, spot cleaner, paint remover
Carbon tetrachloride	30	(5)	125	(20)	Spot cleaner, dry cleaner
Chlorine	3	(1)	9	(3)	Cleaner
Methanol	260	(200)	310	(250)	Paint, spot cleaner
Trichloroethane	1900	(350)	2450	(450)	Cleaning fluid
Methylene chloride	350	(100)	1740	(500)	Paint remover
Trichloroethylene	270	(50)	805	(150)	Dry-cleaning agent
Turpentine	560	(100)	840	(150)	Paint, finish
Xylene	435	(100)	655	(150)	Solvent, paint carrier, shoe dye
Toluene	375	(100)	560	(150)	Solvent, paint carrier, dry cleaning

(a) Data from American Conference of Governmental Industrial Hygienists 1983. Source: Bonneville (1988)

levels of VOCs are likely to increase. On the other hand, if conservation measures such as economizers that increase quantities of outside air are employed, indoor VOC levels are likely to decrease. Morey and Jenkins (1989) found that in 25 problem office buildings, indoor VOC concentrations were just slightly above outdoor levels under economizer conditions. A more thorough discussion of ventilation is contained in Section 3 of this report.

In existing buildings, energy conservation can affect the sources and removal rates of indoor pollutants through inspections and improved maintenance of the building structure and the heating, ventilation, and air-conditioning (HVAC) system. Perhaps the most direct positive effects will be on microbial growth in the HVAC system and on building surfaces. For example,

caulking around windows may eliminate the entry of wind-driven rain, which fosters the growth of molds and fungi (Rask and Lane 1989). Inspections may also reveal microbial growth areas in ductwork near cooling coils, or design deficiencies such as the placement of air intakes near pollutant sources such as garbage storage areas or parking garages (Rask and Lane 1989; Morey 1988).

However, if building inspections result in reductions in ventilation rates, there is likely to be a negative effect on indoor air quality. Field studies suggest that ventilation rates often exceed those specified in ASHRAE Standard 62-1981 (American Society of Heating, Refrigerating and Air Conditioning Engineers, Inc. 1981). Seton, Johnson and Odell, Inc. (1984) conclude that nominal mechanical ventilation rates based on actual occupancy are significantly higher than the design rates listed in Standard 62-1981. Turk et al. (1987) found that in a sample of 40 buildings, on average, overall building air exchange rates ranged from 2 to 8 times the rates recommended for smoking areas in Standard 62-1981. The ventilation rates contained in Standard 62-1981 for smoking areas (as opposed to the ventilation rates listed for nonsmoking areas) are greater than the single ventilation rates listed in ASHRAE Standard 62-1989 (ASHRAE 1989a). Thus, Turk's findings suggest that in existing buildings, overall building air exchange rates exceed both the new ASHRAE Standard 62-1989 and the old ASHRAE Standard 62-1981. If the overall building air exchange rates are reduced to match either of the standards, there is likely to be a negative effect on indoor pollution concentrations.

2.2.7 Specific Mitigation Techniques

Three broad strategies may be employed to reduce VOC concentrations -- source avoidance, source control, and pollutant removal. Each is discussed in the following paragraphs.

Source Avoidance and Substitution - Source avoidance is the most sure method of reducing pollutants. Avoidance of a specific source is generally a one-time measure, requiring no maintenance. A sampling of pollutants that may be emitted by building materials is presented in Section 2.2.2. Avoidance can be achieved through the use of product standards that restrict the application of specific high emitters, or through architects and engineers specifying the use of low-emitting building materials. Levin (1989b) has developed sample

specifications to avoid some pollutant sources. Reports suggest that catalogs will soon be published as a compendium of EPA and DOE research in this area to guide in the selection of materials with low pollution potential (McNall 1988). An example of a product standard is the HUD formaldehyde standard, which was discussed in Section 2.2.5.

Source Control - If sources of VOCs must be used, they may be controlled with spot ventilation, such as exhaust hoods over work benches, or with barriers. Effective barriers that block formaldehyde emissions include polyethylene plastic, vinyl linoleum, paints, shellac, varnishes, or lacquer. However, the coatings must be continuous and remain intact to be effective, and in their own right may be a source of VOCs. Barriers for other types of pollutants are not well understood.

Another approach to controlling occupant exposure to emissions is to minimize the quantity of the source introduced to the building and introduce the source in off-hours when the fewest people will be affected. One technique for reducing emissions is to condition building materials or furnishings before installation. Conditioning could be accomplished by airing out material, possibly in combination with elevated temperatures (Seifert et al. 1989).

Pollutant Removal - Ventilation is a good method of dissipating pollutants. Sheldon et al. (1988a) found that the half-lives of the compounds found in two new office buildings ranged from 2 to 8 weeks, and the time for the building to approach outdoor VOC concentrations would range from 3 to 12 months. Sheldon states that these findings compare well with the Scandinavian decision to require 100% makeup air for the first 6 months of a new building's life (Sheldon et al. 1988a).

Girman et al. (1987, 1989) report on a process called "bake-out" as a potential mitigation technique for high VOC levels in new commercial buildings. The procedure involves subjecting the indoor environment to high temperatures and high ventilation rates to encourage the emission and removal of VOCs. A building in San Francisco was heated to a maximum of 39°C (102°F) for 24 hours, at a ventilation rate of 1.59 air changes per hour (ACH). Fourteen VOCs were quantified. The total VOC concentration increased by 400% during

the bake-out, and was reduced to 71% afterwards. Girman concludes that longer bake-out periods may be more effective. In addition to demonstrating the effectiveness of this mitigation technique, Girman's work underscores the important role of temperature, aging, and ventilation in influencing VOC concentrations.

2.3 RESPIRABLE SUSPENDED PARTICULATES

Respirable suspended particulates (RSP) are particles or fibers in the air that are small enough to be inhaled. They are a broad class of chemically and physically diverse substances and can be in either a solid or liquid phase, or in combination. They are generally less than 10 μm in diameter (DOE 1986).

Respirable suspended particulates are generated from building materials (fiberglass fibers, cellulose fibers, asbestos fibers), combustion devices (gas appliances, gas hot water heaters, and boilers), occupant activities (tobacco smoke, resuspended dust), and infiltration from outdoor sources (atmospheric dust, combustion emissions from mobile and stationary sources). However, the largest single source of RSP in the indoor environment is tobacco smoke (Mueller Associates, Inc., et al. 1987; Turk et al. 1986).

Asbestos is a collective term for a variety of asbestiform minerals, each of which satisfies a particular industrial-commercial need. These include chrysotile, anthophyllite, riebeckite, cummingtonite-grunerite, and actinolite-tremolite. Commercial names for the first four of these are chrysotile, crocidolite, anthophyllite, and amosite. These minerals differ in chemical composition, but all are silicates. Chrysotile accounts for over 95% of the asbestos sold in the United States (Godish 1989). Asbestos fibers are characterized by their small diameter, high length-to-width ratio, and great strength and flexibility.

Health risks from RSPs can be attributed to either their intrinsic toxic chemical or physical characteristics, as in the case of asbestos, or to the particles acting as a carrier of adsorbed toxic substances, as in the case of radon (see Section 2.6). Because they can deliver a high concentration of harmful substances deep in the lungs, RSPs present a health risk out of

proportion to their concentration in air. Once in the lungs, they have a long residence time, affording a greater opportunity for surrounding tissue to become affected.

2.3.1 Pollutant Sources and Source Strength

Indoor sources of RSPs include combustion sources (fireplaces, wood stoves, unvented gas appliances), asbestos construction materials, and house dust. Other incidental indoor sources include the use of aerosol sprays, and wear and sloughing of building material. In the office environment, photocopy dust may also contribute to elevated levels of RSPs (Turk et al. 1986; Mueller Associates, Inc., et al. 1987). Some RSPs are from outdoor sources and enter the building interior via the HVAC system or through natural ventilation and infiltration.

Combustion Byproducts - Wood stoves and gas burners contribute to indoor RSP levels. Gas ovens and gas and kerosene space heaters contribute very little to overall RSP levels. Table 2.11 presents a summary of the particulate emissions rates for various combustion sources.

Tobacco Smoke - More than 95% of the particulates produced from tobacco smoking are from sidestream smoke. Sidestream smoke arises from smoldering tobacco. Particulate emissions from sidestream smoke are estimated to be as much as 30 to 40 mg per cigarette (Mueller Associates, Inc., et al. 1987).

TABLE 2.11. Pollutant Emission Rates (adapted from Mueller Associates, Inc., et al. 1985)

Source	Appliance Type	Emission Rate (mg/hr)
Kerosene Space Heaters	Radiant	0.13 - 0.16
	Convection	<0.03 - 0.034
Gas Space Heaters	--	0.21 - 3.23
Wood Heater		2.6
Gas Appliance	Range (1 burner)	1.9 - 30
Oven		118 - 0.126

Fiberglass and Cellulose Fibers - Fiberglass RSP can be generated from the insulation used in ventilation ducting. Gamboa (1988) found that fiberglass fibers released from Type 475 duct board and fiberglass duct liner were typically well below the 3.0 fibers/cm^3 permissible exposure limit proposed in 1977 by NIOSH. However, these releases still resulted in fiber levels approximately twice normal background concentrations.

Asbestos - Commercial use of asbestos is extensive, with over 3000 applications, including fireproofing, thermal and acoustical insulation, acoustical plaster, friction products such as motor vehicle brake shoes, reinforcing material in cement water pipe, and roofing and floor products. Asbestos can be found in most large public access buildings, including schools, office buildings, and commercial buildings. Vinyl floor covering may also contain asbestos fibers, but historically it is not considered a significant source of asbestos because of the bound nature of the material (Godish 1989), except when it is disturbed, as during remodeling or removal.

Asbestos is used as thermal insulation around steam lines and boilers. In this situation, it is less of a threat for fiber release into occupied spaces and exposure to humans, because it is usually covered with a rigid cloth or paper material and is often inaccessible to most building occupants.

Asbestos release to the indoor environment depends on the cohesiveness of the asbestos-containing material (ACM) and the intensity of the disturbing force. Most contamination is episodic and activity-related (Mueller Associates, Inc., et al. 1987). The greatest threat for human exposure is from fiber release from surface materials as they age and the binding material weakens.

Prior to 1973, it was a common practice to apply ACMs by spraying or troweling to a variety of building surfaces, notably ceilings and steel beams. The use of such friable ACMs as a fire/heat retardant in public schools and other large buildings has been banned by the EPA in an effort to reduce community exposure to asbestos fibers during building demolition (Godish 1989).

2.3.2 Concentrations in Commercial Buildings

Generally, RSP concentrations are greater indoors than outdoors. Typical indoor RSP concentrations range from 100 to 500 $\mu g/m^3$, with the highest concentrations occurring in areas with tobacco smoking. Although wood and kerosene-burning appliances can contribute to higher levels of RSP in the indoor environment, other sources such as cooking, vacuum cleaning, aerosol spray products, and other activities are significant sources of indoor RSP (Saxton 1984).

Combustion Byproducts - A study conducted in 10 paired homes in Boise, Idaho, found that normally functioning wood stoves contributed 4 to 16 $\mu g/m^3$ to total RSP levels. Damaged or improperly operated stoves contributed over 70 $\mu g/m^3$ to the RSP levels (Highsmith et al. 1988). The Mueller Associates, Inc., et al. (1987) reported RSP levels in residences using wood-burning appliances ranging from 10 to 100 $\mu g/m3$.

Although indoor concentrations of RSP in wood-burning residences tends to be higher than in non-wood-burning residences, the difference is not statistically significant (reflecting the high variability in indoor concentrations).

Kerosene heaters can raise short-term concentrations to 100 to 300 $\mu g/m^3$ (Godish 1989), depending on the type, age, and use pattern.

Tobacco Smoke - In a study conducted in 38 commercial buildings in the Pacific Northwest, the geometric mean of RSPs in all buildings was 24 $\mu g/m^3$. The geometric means for smoking areas and nonsmoking areas were 44 $\mu g/m^3$ and 15 $\mu g/m^3$, respectively. Fourteen of the 70 smoking sites and only one of the 106 nonsmoking sites exceeded the ASHRAE annual exposure guideline of 75 $\mu g/m^3$. The highest level of 308 $\mu g/m^3$ occurred in a Portland office building cafeteria where smoking was allowed (Turk et al. 1986).

Even in buildings with local high indoor RSP levels due to tobacco smoke, nonsmoking areas of the same building can be quite low. In the above study, in only one building were RSP concentrations in the nonsmoking area within a factor of 2 of the smoking area concentrations. Local exhaust, ventilation near smoking areas, dilution by large building volumes, and

removal mechanisms significantly reduce RSP concentrations in areas away from the source (Turk et al. 1986). However, in buildings with smaller volumes and poor ventilation, isolating smoking areas may have little effect at limiting the distribution of RSPs.

Fiberglass and Cellulose Fibers - No information could be located that specifically addressed concentrations of fiberglass and cellulose fibers.

Asbestos - Ambient concentrations of asbestos range from 0.00005 to 0.00022 fibers/cm^3. Concentration in public buildings and schools ranged from 0.00026 to 0.0040 fibers/cm^3 (Godish 1989). In nonresidential situations, asbestos concentrations range from 0.02 fibers/cm^3 (falling from exposed asbestos ceiling) to 17.7 fibers/cm^3 (during ceiling repair). During the mixing of drywall taping compounds, fiber counts measured were found to be from 7 to 12 times greater than the current occupational standard (Mueller Associates, Inc., et al. 1987).

2.3.3 Environmental Factors

Natural removal mechanisms for RSP include physical deposition, chemical transformation, and particle agglomeration. Chemical transformation of the nonfibrous particulates increase with increasing temperature. Higher relative humidities encourage the agglomeration of some airborne RSP into larger particles, accelerating their settling rate, as well as converting them into particles that are less likely to be inhaled. Although the larger particles may be inhaled, they will be deposited in the nose/mouth and not deep in the lungs.

2.3.4 Standards, Guidelines, and Regulatory Effects

Except for asbestos, a specific U.S. standard for RSP does not exist. The Occupational Safety and Health Administration (OSHA) has set an 8-hour time-weighted average limit of 5000 $\mu g/m^3$ for respirable inert or nuisance dust. The EPA established a 24-hour ambient air quality standard for particulates less than 10 μm in diameter (referred to as PM_{10}) at 150 μ/m^3. The ASHRAE total suspended particulate (TSP) annual exposure limit is 75 $\mu g/m^3$. Because RSP is a subset of the TSP, the ASHRAE limit can also be used as a conservative guideline for RSP.

The OSHA-established asbestos standard is less than 2 fibers longer than 5 μm per cm^3 for an 8-hour time-weighted average.

2.3.5 Interactions with Energy Conservation Measures

Building/system components that most significantly influence the indoor levels of pollutants include 1) envelope construction material and technique, 2) infiltration and natural ventilation, and 3) control and operation of the mechanical ventilation system. Energy conservation measures (ECMs) that alter or in any way affect any of these components will, either directly or indirectly, affect indoor RSP levels. A direct effect is one in which the ECM either increases or decreases the source emanation rates. An indirect effect is one in which the pollutant concentrations are increased or decreased. For example, in the absence of a strong indoor source (e.g., tobacco smoke), any ECM that results in a net reduction of natural infiltration will likely reduce indoor RSP concentrations due to the reduction of the rate of infiltration of outdoor particulates (i.e., fugitive dust) to the indoor environment. On the other hand, when major indoor sources are present, ECMs that reduce the rate of infiltration will most likely result in greater indoor RSP concentrations because of reduced dilution with fresh air.

In existing, older commercial buildings, any activity that disturbs existing ACMs will result in increased levels of asbestos fibers. Although the disturbing activity is only temporary, resuspension of the fibers due to normal occupant activity can result in elevated levels of RSP.

The paragraphs below describe the effects of ECMs on indoor levels of RSP by building system component.

Building Envelope - Installation of additional insulation in the walls, ceiling, roof, foundation, or slab can directly increase the levels of RSP/fibers by increasing the source of fiberglass/cellulose material in the building.

Any ECMs designed to decrease infiltration/exfiltration by modifying the building envelope will indirectly affect the levels of RSP. For RSPs with indoor (outdoor) sources (such as combustion byproducts), the RSP levels will be increased (decreased) due to the decreased rate of dilution of the

pollutant with fresh air. These ECMs include 1) weatherstripping and caulking, 2) installation of storm doors and windows, 3) enclosing loading docks with shelter and seals, 4) installation of vestibules, and 5) sealing vertical shafts.

HVAC System - The only HVAC ECM that will affect indoor RSP/fiber levels will be the installation of duct insulation. One study suggests that the relative increase in fiber levels can be large, although normal background levels are generally low and it is unlikely any standards will be exceeded.

Ventilation - Recirculation of exhaust air using activated carbon filters has the potential for directly increasing RSP/fiber levels by increasing the opportunity for fiber release within the building. This same ECM, however, will also remove RSPs (including fibers) from the indoor air as they are recirculated through the ventilation system.

The installation of vortex hoods in the kitchen areas of restaurants will effectively remove much of the combustion byproduct RSPs generated by the gas burners, thereby reducing RSP levels in the remainder of the building.

2.3.6 Specific Mitigation Techniques

Mitigation techniques for controlling RSPs fall into three broad categories: source control, ventilation, and air cleaning. A generic description of these techniques is presented in Section 4.

More specific control technologies for RSP include the following (Mueller Associates, Inc., et al. 1987):

- Limit or eliminate smoking tobacco indoors.
- Make sure wood stove doors and flues do not leak.
- Supply outdoor air directly to wood stove and fireplace firebox.
- Use electrostatic precipitators and high-efficiency particulate air (HEPA) filters as effective removal media.
- Change air filters regularly.
- Vent combustion appliances outdoors.

Air cleaners for particulate control are available as both in-duct devices or stand-alone devices for single room use. Particulate air cleaners can be divided into two groups: mechanical filters and electrostatic filters. Mechanical filtration is generally accomplished by passing the air through a fibrous medium. Electrostatic filtration operates on the principle of attraction between opposite electrical charges. Ion generators and electrostatic precipitators use this principle for removing particles from the air.

For asbestos, source control is the only acceptable mitigation option. This is a reflection of its hazardous nature and the compelling need to prevent asbestos fibers from becoming airborne. Special asbestos abatement measures include repair, enclosure, encapsulation, and removal. The EPA considers removal the only permanent solution and recommends the use of enclosure or encapsulation only under limited circumstances (Godish 1989).

2.4 BIOLOGICAL CONTAMINANTS

Biological contaminants are either living organisms (bacteria, fungi, viruses, amoebae, algae, and pollen grains) or the byproduct of living organisms. The organism byproducts include plant parts; insect parts and wastes; animal saliva, urine, and dander and human dander; and a variety of organic dusts (Godish 1989).

The source of biological contaminants can be either in the indoor environment or outdoors, and transported indoors via infiltration and/or through the building's ventilation, air-conditioning, and humidifying systems. Indoor surface contamination by bacteria, fungi, insects, arachnids, or other biological particles usually will not have adverse health effects until the particles become airborne and are inhaled (Burge 1985).

Biological contaminants can produce direct toxicity (as in the case of some molds), or they may be pathogenic (provoking infectious disease) or allergenic (provoking hypersensitive or allergic disease). The majority of biological contaminants are nonpathogenic and cause adverse health effects only in individuals who are sensitive to that particular contaminant, such as allergic reaction to plant pollen. Even many pathogenic microorganisms are able to infect only susceptible individuals (Burge 1985). Even though there

is a lack of understanding about the magnitude of the health effects caused by exposure to biological contaminants, the consequences of some are appreciable. For example, the most common respiratory disease attributable to allergens is allergic rhinitis (allergies), which affects approximately 15% of the U.S. population (Mueller Associates, Inc., et al. 1987).

Hospitals and other exceptional "clean" room environments have their own unique requirements and are not addressed in this document.

2.4.1 Pollutant Sources and Source Strength

The paragraphs below describe the various sources of biogenic contaminants. No information is available on the source emanation rates.

The two most important allergen contaminants found in indoor air that are known to cause both allergies and asthma are produced by dust mites and fungi (Godish 1989). The most severe indoor biological contamination results from growth of the offending organism on surfaces within structures, such as cooling towers and condensate drip pans on air conditioners. Virtually any surface that includes both a carbon source and a supply of water will support the growth of some microorganism.

Many buildings with biological contamination can trace the probable cause to the lack of proper maintenance of the HVAC system. Typical maintenance problems include condensate drains and drip pans that are not cleaned, filters that are not cleaned or replaced, and dirt and biological growth in the duct system (Robertson 1989).

The primary source of indoor bacteria is the human body. Although the major source is the respiratory tract, it has been shown that 7 million skin scales are shed per minute per person, with an average of four viable bacteria per scale (Mueller Associates, Inc., et al. 1987).

Cool mist vaporizers and nebulizers can produce heavily contaminated aerosols. Other potential sources of indoor bacterial aerosols include ice machines, commercial dishwashers, air conditioners, and humidifiers (Mueller Associates, Inc., et al. 1987). Flush toilets and urinals surely aerosolize bacteria, but do not pose great disease risk unless they are heavily

contaminated and poorly maintained (Burge 1985). Pathogenic microorganisms are spread by the use of the same air-conditioning and humidifying equipment that can be the source of the contaminant.

High mold levels in office buildings can result from mold growth in cooling coil drip pans found in HVAC systems, in evaporative condensers, and on water-damaged materials.

Many bacteria, including *Legionella pneumophila* (Legionnaires' Disease), thrive in outdoor natural reservoirs, and infection is possible through inhalation of contaminated outdoor air. The most common mechanism for spreading bacteria is air-cooling equipment that is contaminated and produces concentrated bacterial aerosols (Mueller Associates, Inc., et al. 1987).

Most fungi are primary decay organisms and are abundant on dead or dying plant and animal materials. Thus, natural wildlife habitats, parks, and green spaces near buildings will surely lead to some indoor contamination and possible risk of infection. The extent of contamination from fungi is unknown, but some are known to be highly infectious.

2.4.2 Concentrations in Commercial Buildings

Building entry of biological contaminants from the outside is through cracks, windows and doors, or through ventilation, air conditioning, and humidifying systems. Rate of entry is determined by indoor/outdoor pressure differentials, quantity, and type of ventilation, wind conditions, temperature, and humidity (Baechler et al. 1989).

During the growing season, outdoor fungus spore levels exceed those indoors. Only in cases of extreme indoor contamination do indoor spore levels exceed outdoor levels (Burge 1985).

Extensive, quantifiable data on indoor concentrations in the case of microorganisms, allergens, and pathogens is limited (Mueller Associates, Inc., et al. 1987). In one study, air sampling in seven office buildings in New York City for mesophilic fungi, Morey and Jenkins (1989) found that in most buildings the indoor concentrations of fungi during normal periods of occupancy were approximately 10% to 25% of coincident outdoor concentrations. However, during periods when furnishings and the HVAC system components were

disturbed, concentrations of airborne fungi in the immediate vicinity generally exceeded outdoor levels by a factor 1.5 to 13. In one building, the indoor concentrations exceeded outdoor levels by a factor of 100. Outdoor fungi levels ranged from a low of 36 colony-forming units per cubic meter of air (cfu/m^3) to over 800 cfu/m^3.

2.4.3 Environmental Factors

Ideal growing conditions for microorganisms such as spores, molds, and fungi include moisture, humid air, and warm temperatures. Microorganisms require humidity in the range of 25% to 70% to increase in number. Above 70% is optimal for growth of molds and bacteria and for the survival of airborne pathogens (Mueller Associates, Inc., et al. 1987; Burge 1985). The lowest relative humidity at which a fasting mite can sorb sufficient water to maintain water balance is 70% to 73%. This condition must be met or mite population cannot survive (Godish 1989).

Skov and Valbjorn (1987) and Valbjorn and Skov (1987) found no association between SBS and ventilation characteristics, but did find strong positive correlations with the age of the building, the total weight and potential allergenic portion of floor dust, the area of fleecy material, the open shelving per cubic meter of air, and the air temperature.

Air currents produced by convection from radiant heat and by air mechanically circulated by forced air systems are more than adequate to spread dust (including entrained biological particles), as well as mobilizing surface growth (Burge 1985).

2.4.4 Standards, Guidelines, and Regulatory Effects

There are no standards or guidelines established for biological contaminants in commercial buildings. However, for some hospital operating rooms, the upper concentration limit for particulates containing viable bacteria has been set at 175 particles/m^3 (Morey 1985).

2.4.5 Interactions with Energy Conservation Measures

Energy conservation measures that directly or indirectly affect the sources of biological contaminants or the concentrations of contaminants in the indoor air are described below by building/system component.

Building Envelope - Any of the building envelope ECMs that are designed to reduce infiltration/exfiltration through envelope sealing will likely have the net effect of reducing indoor levels of biological contaminants from outdoor sources by reducing the transport of contaminated outdoor air to the indoors.

For indoor sources, shell-tightening measures will likely increase indoor concentrations by reducing contaminant dilution. Research conducted on military barracks suggests that tight buildings with closed ventilation systems significantly increase the risks of respiratory-transmitted infections among congregated, susceptible occupants (Brundage et al. 1988).

Potential ECMs that will reduce infiltration include

- caulking and weatherstripping
- installing storm doors and windows
- enclosing loading docks with shelters and seals
- installing vestibules
- sealing vertical shafts.

HVAC System - Many of the potential HVAC system ECMs will directly increase the potential for biogenic contamination, particularly for the bacteria contaminants that develop in water reservoirs. These ECMs are

- replacing air-cooled condenser with wet cooling tower
- installing roof spray systems
- installing spot cooling.

These three ECMs either use water directly or will indirectly generate water as condensate that can collect in drip pans, basins, and other containers. If not properly maintained, the water reservoirs will become contaminated with microorganisms.

Ventilation - Installing evaporative cooling of outside air will directly increase the threat of bacterial contamination by increasing the breeding ground for bacteria. Any of the ECMs that will reduce ventilation

and/or increase the use of untreated recirculating air could amplify the concentration of microorganisms. These include

- reducing ventilation automatically during unoccupied periods
- recirculating exhaust air using carbon activated filters
- installing dual-speed fans (if the net effect is an overall net reduction in air circulation).

Installing a carbon dioxide (CO_2)-controlled ventilation system may decrease levels of biogenic contaminants during periods of building occupancy by increasing ventilation rates over "normal" rates.

2.4.6 Specific Mitigation Techniques

Biological contaminants are best controlled by applying a variety of source control measures, primarily focusing on restricting the availability of moisture necessary for microorganism growth. Removal of nutrients needed for microbiological growth may also control contamination. Air cleaning can be of limited effectiveness (Burge 1985; Mueller Associates, Inc., et al. 1987; Baechler et al. 1989).

Source prevention is essential for control of microorganisms. Source control strategies fall into two broad categories: 1) initial system design that minimizes the potential for microbial growth and subsequent contamination of building air-handling systems, and 2) preventive maintenance, including adherence to routine inspection and proper maintenance of all existing water-using or -generating systems associated with the HVAC system.

From a systems perspective, humidification units based on recirculated water should not be used. Steam as a moisture source is preferred (Godish 1989). If cool water humidifiers are to be used, water should originate from a potable source and run to a drain instead of being recirculated. The system should be regularly inspected, cleaned, and disinfected.

Cool-mist vaporizers, such as found in grocery store produce areas, have recently been linked with the bacteria *Legionella pneumophila*.

Elimination of the use of water-spray systems in office building HVAC systems, restriction in the use of humidifiers, proper location of cooling

towers with respect to building vents, and the utilization of available filtration-air disinfection devices have been advocated as control measures for specific indoor environments.

Preventive maintenance or housekeeping activities, together with protection from floods and moisture incursion, will reduce the chance of microbial contamination in the indoor environment. Stagnant water should not be allowed to accumulate in cooling coil condensate drip pans. Drip pans should be properly inclined to provide continuous drainage (Godish 1989). Plumbing and other fluid systems should be maintained so that no water incursions occur in the building. If incursions do occur, they should be rapidly cleaned up and water-damaged materials discarded. Water-damaged material (such as ceiling tiles and carpeting) that has become contaminated with microorganisms should be discarded and replaced.

Relative humidity less than 50% is necessary to keep mold levels below average (Burge 1985). Maintaining relative humidity levels as low as reasonably achievable, while consistent with occupant comfort, can be an effective control strategy. In kitchens and other normally high moisture areas where it is not possible to lower humidity levels, maintenance and cleaning of water reservoirs becomes even more important as a control strategy to prevent microorganism proliferation.

Mitigation measures involving actual air cleaning fall into two categories: reducing outdoor influx of contaminants and removing contaminants from indoor air. However, air cleaners produce limited results. In most situations where air cleaners are used, there are continuing sources (outside air, dust, people) and the cleaners reach a balance between the effective rate of removal and the rate of contaminant generation. Unfortunately, the balance is usually not on the side of clean air (Burge 1985).

Antimicrobial agents are less effective in preventing contamination than the basic environmental changes discussed above. They can be useful in cleaning known sources, but unless the basic conditions causing the initial contamination are changed, recontamination will occur (Burge 1985).

2.5 COMBUSTION GASES

Combustion gases, such as carbon monoxide (CO), carbon dioxide (CO_2), nitrous oxide (NO), nitrogen dioxide (NO_2), and sulfur dioxide (SO_2) can be introduced into the indoor environment by a variety of either indoor or outdoor sources. For the purposes of this report, environmental tobacco smoke (ETS) is included along with the other combustion byproducts that contribute to the gaseous contamination of indoor air. Smoking of tobacco products indoors is the major source of combustion-generated contaminants found in indoor air (Godish 1989). More than 2000 gaseous compounds have been identified in cigarette smoke (Mueller Associates, Inc., et al. 1985, 1987).

2.5.1 Pollutant Sources and Source Strength

Combustion gases are introduced into the indoor environment from either indoor combustion sources or from outdoor sources, such as attached parking garages. The description of the sources of combustion gases presented below is adapted from Mueller Associates, Inc., et al. (1985).

Nitrogen Oxides (NO_x) - Indoor levels of NO_x are primarily affected by gas stoves, unvented kerosene and gas space heaters,and, to a lesser degree, tobacco smoking. Wood stoves do not usually produce significant emissions of NO or NO_2. Emission rates for NO_x from appliances are shown in Table 2.12. The emission rate of NO_x from tobacco smoking is 0.06 to 0.73 mg/cigarette. Infiltration of NO_x from outdoor sources is significant in heavily populated, industrialized urban areas where fossil fuel combustion and vehicles emissions are major outdoor sources of NO_x.

Carbon Monoxide - Carbon monoxide is formed whenever fuel is incompletely burned. The CO concentration in the indoor environment is mostly a result of combustion appliances such as gas stoves, portable kerosene and gas space heaters, and wood stoves. Tobacco smoking is a lesser source. Outdoor sources of CO, including emissions from vehicles in attached garages, also contribute to indoor levels of CO. The CO emission rate for tobacco smoking is 52 to 105 mg/cigarette.

TABLE 2.12. Emission Factors for Gas Appliances (adapted from Borrazzo et al. 1985)

Appliance	CO (μg/sec)	NO (μg/sec)	NO_2 (μg/sec)
Range Burner			
1-hour ave - high	350	33	45
- medium	390	25	38
- low	360	10	23
steady-state - high	260	37	43
- medium	360	26	38
- low	320	10	23
Oven			
400°F, 0-15 min	760	100	108
400°F, 15-60 min	84	36	26
500°F	86	58	40
Pilot lights	14	1	2
Furnace	<10	2	1
Water Heater	<10	38	6
Clothes Dryer			
Fugitive emissions	<10	2	1
Exhaust emissions	110	110	71

Carbon Dioxide - The single greatest contributor to indoor CO_2 is human metabolic activity. Significant quantities of CO_2 are also generated by gas stoves and portable kerosene and gas space heaters, and can be introduced to the indoor environment if not vented properly. Wood stoves and tobacco smoking produce smaller amounts.

Sulfur Dioxide - Indoor SO_2 is usually a result of infiltration of SO_2-contaminated outdoor air, primarily from stationary fuel combustion and industrial processes. Vehicle emissions contribute a smaller amount. The only significant potential indoor sources are portable kerosene space heaters and leaky flues in buildings where sulfur-containing fuel is burned. Emission rates for kerosene heaters range from 30 mg/hr to over 100 mg/hr.

Benzo[a]pyrene (BaP) - Indoor concentrations of BaP are a result of wood combustion and tobacco smoking. Outdoor concentrations of BaP as an indoor source appear to be insignificant.

The rates at which combustion gases are introduced into the indoor environment from appliances are summarized in Table 2.12.

2.5.2 Concentrations in Commercial Buildings

For intermittent sources, source emission rate, building volume, and rate of mixing are the primary factors affecting peak concentrations. For continuous sources, source emission rate and duration, the outdoor concentration, and air exchange rate are the primary factors affecting long-term average concentrations (Mueller Associates, Inc., et al. 1985). Numerous studies do not offer clear evidence that combustion gases can reach concentrations substantially higher than ambient concentrations (Spengler and Cohen 1985).

Nitrogen Oxides - In a Bonneville study of 38 commercial buildings in the Pacific Northwest, a total of 245 sample locations in 33 buildings were tested for NO_2. The geometric mean of all sample locations was 18.3 ppb, with a standard deviation of 1.7 (9% of the mean). Smoking areas had a geometric mean of 20 ppb. Only two monitoring locations in two different buildings had NO_2 levels greater than the EPA ambient air quality standard of 50 ppb. One was a 58-ppb average with a building average of 22 ppb, and the other was in a building known to be contaminated with vehicle exhaust emissions (Turk et al. 1986).

Carbon Monoxide - In the same Bonneville study, only six of 32 buildings monitored for CO had a time weighted average concentration greater than the minimum detectable level of 2 ppm (Turk et al. 1986). For these six buildings, the means ranged from 2.1 ppm to 3.3 ppm. Three of the six buildings had underground parking.

Turner (1988) seldom found CO levels greater than 9 ppm in buildings monitored in Australia, the United Kingdom, and the United States.

In a survey of CO concentrations in 25 individual stores in a large shopping center in Honolulu, Hawaii, OSHA's 1-hour standard of 200 ppm was not exceeded at any of the sample outlets on any survey date. The National

Ambient Air Quality Standard (NAAQS) of 35 ppm for 1 hour was exceeded on at least 18 of the 30 (60%) survey dates. Hawaii's Ambient Air Quality Standard (AAQS) of 9 ppm was exceeded on every survey date at many outlets. The OHSA's 8-hour CO standard of 50 ppm was not exceeded on any survey date. However, 21 of the 25 outlets (84%) had 30-day averages exceeding the NAAQS of 9 ppm, and 23 of 25 outlets (92%) had 30-day CO averages exceeding Hawaii's AAQS of 4.5 ppm. Average CO levels were 3 to 23 ppm inside the 25 street-level outlets. Motor vehicle emissions of CO were believed to be the primary source. In restaurant and fast-food establishments, gas-fired stoves and ovens were expected to be another source of CO (Flachsbart and Brown 1985).

Carbon Dioxide - In a study of commercial buildings in the Pacific Northwest, 39 8-hour average CO_2 measurements were made in 37 buildings. Concentrations were found to be dependent on occupancy levels. Only one 15-minute CO_2 reading in a crowded elementary school classroom exceeded 1000 ppm (1290 ppm). Periods of low occupancy (recess and lunch) were evident in the time series data. Four buildings had instantaneous CO_2 maxima over 800 ppm. Eight-hour averages ranged from 337 ppm to 840 ppm (Turk et al. 1986).

General office area CO_2 levels have been found by Turner (1988) to range from 350 ppm to 2000 ppm.

Sulfur Dioxide - No information was found describing SO_2 concentrations in commercial buildings, but they are believed to be generally low. The only exception would be if kerosene space heaters are used extensively.

2.5.3 Environmental Factors

Two major environmental factors that can influence the contribution of ambient (outdoor) levels of combustion-related gases to indoor contaminant levels and location and time (Mueller Associates, Inc., et al. 1985):

- The location of a building relative to major outdoor sources can affect indoor air quality. Depending on the emission rates, air pollutants from stacks, flues, vents, and cooling towers can also affect the indoor air quality. Buildings located near major streets or highways may be affected by the gaseous pollutants generated from vehicles. In general, urban and industrialized areas have higher concentrations than rural areas.

- Temporal fluctuations in concentration of outdoor gaseous pollutants will also influence indoor concentrations. Diurnal or seasonal patterns and day-to-day variations in the weather and daily variations in emission rates all determine ambient concentrations.

Pollutant reactivity can be, in some cases, as important as air exchange rates in reducing indoor combustion gas concentrations, especially when the air exchange rate is low. Nitrogen dioxide is removed through chemical reaction. Carbon monoxide may be adsorbed on indoor surfaces, and particulate matter will be deposited on indoor surfaces. The rate at which reactions occur varies for each pollutant and is influenced by temperature, moisture, presence of other compounds, and types of surfaces found (Mueller Associates, Inc., et al. 1985).

Combustion byproducts may be removed from the indoor atmosphere by a number of mechanisms other than air exchange. Individual pollutants may be reduced by one or more of the following physical or chemical reactions: adsorption, absorption, conversion, and deposition. Indoor-combustion-generated pollutants are modified by these reactions as follows:

- nitrogen oxides - NO_2 is removed through reaction; NO may be adsorbed on surfaces.

- carbon monoxide - CO is comparatively inert, but may be adsorbed on indoor surfaces.

- sulfur dioxide - The SO_2 concentration may be reduced by the oxidation of SO_2 to sulfate particles or by dry deposition on surfaces. SO_2 interacts with airborne particles primarily by adsorption.

A number of environmental factors will affect the rate at which reactions occur indoors, which will, in turn, affect the rate of removal of pollutant concentrations.

- temperature - The rates of most chemical reactions increase with temperature. The rate of reaction will roughly double for each 10°C rise in temperature

- moisture - The moisture in the air can enhance pollutant deposition rates. This is true for gases such as SO_2.

- solar radiation - Some reactions require the presence of sunlight. Decomposition of NO_2 to NO and ozone (O_3) requires sunlight.

- presence of other compounds - Reactions are affected by the presence or absence of certain compounds.

- surfaces - Some air pollutants differ in stability between indoors and outdoors because of the variety of surfaces found indoors on which reactive compounds adsorb and decompose. For example, O_3 is decomposed especially quickly indoors. This is also somewhat true for SO_2 and NO_2, while CO and NO are less reactive.

2.5.4 Standards, Guidelines, and Regulatory Effects

The Occupational Safety and Health Administration has established regulations governing the exposure of workers to toxic and hazardous substances in the workplace. These standards are listed in Table 2.13.

2.5.5 Interactions with Energy Conservation Measures

In public buildings without indoor combustion sources, no significant increase in indoor-combustion-related pollution levels is expected to occur with reduced ventilation rate. A single exception is CO_2 from human metabolic activity, which was still below levels considered a health hazard. Indoor air quality improved for outdoor generated sources.

In general, lower air exchange rates result in higher concentrations of contaminants from indoor sources. However, concentrations of reactive pollutants such as NO_2 and RSP may not be directly related to the air exchange rate. The air change rate plays an increasing role with time and has relatively little effect on initial peaks in the indoor pollutant concentrations (Mueller Associates, Inc., et al. 1985).

TABLE 2.13. OSHA Standards for Combustion Gases

Pollutant	Standard ppm	Standard mg/m^3	Time Interval
CO_2	5000	9000	8-hour time-weighted average
CO	50	55	8-hour time-weighted average
CO	200	220	1-hour average
NO	25	30	8-hour time-weighted average
NO_2	5	9	Ceiling value
SO_2	5	13	8-hour time-weighted average

Specific energy conservation measures that will affect combustion-related contaminant levels in commercial buildings are described below.

Building Envelope - Any ECMs that will tighten the building envelope will reduce the contribution of outdoor contaminants to the general level of pollutants indoors. However, in the presence of strong indoor sources, these same ECMs will tend to increase indoor contaminant levels due to reduced exfiltration rates and dilution with fresh air. These ECMs include

- caulking and weatherstripping
- installation of storm doors and windows
- enclosing loading docks with shelters and seals
- installing vestibules
- sealing vertical shafts.

HVAC System - None of the HVAC system ECMs will affect indoor concentrations of combustion gases.

Ventilation - The installation of variable rate, CO-controlled exhaust ventilation systems in covered parking garages will reduce indoor levels of CO by reducing the primary outdoor source of CO in buildings with attached parking garages. Installation of vortex hoods in the kitchen areas of restaurants will reduce levels of contaminants from gas stoves by effectively removing the contaminants at the source. Other ECMs that affect the ventilation system will have only minor impacts on indoor air quality.

2.5.6 Mitigation Techniques

In general, source removal is the most effective way to control indoor pollutant levels (Mueller Associates, Inc., et al. 1985). Increasing whole-building ventilation causes a smaller decrease in the concentration of a reactive pollutant such as NO_2 than nonreactive pollutants (Mueller Associates, Inc., et al. 1987). Local exhaust ventilation in the vicinity of a pollutant source is an effective source specific ventilation control technique (Kandarjian 1988). Air cleaning devices and the use of new, less polluting technologies can also be used to mitigate (Mueller Associates, Inc., et al. 1985).

It appears that the most practical long-term solution to minimizing the effects of tobacco smoking and to minimize the buildup of CO_2 from occupant

metabolism is to ventilate office buildings to the ASHRAE Standard 62-1989 requirement of 20 cfm of outside air per person.

2.6 RADON

Radon is an inert, radioactive gas that occurs naturally in the environment as a decay product of radium. It, in turn, decays to form radioactive progeny that may attach to dust particles or remain unattached. If these progeny are inhaled, they can be drawn into the lungs, where they emit alpha energy which may lead to lung cancer.

Ambient concentrations of radon are generally low due to dilution with large volumes of outdoor air. Typical indoor concentrations can be as much as an order of magnitude greater than outdoors, and can exceed three orders of magnitude.

2.6.1 Pollutant Sources and Source Strength

Primary sources of radon and radon progeny in buildings are soil gas from the soil adjacent to the building, potable water, and building materials.

Soil - The amount of radon entering a building is dependent on the adjacent soil radium content and porosity, as well as the building construction type. Radon-bearing soil gas is transported into the building by pressure-induced convective flows. The EPA has estimated that the average soil contains about 1 ppm of uranium. Phosphate rock contains 50 to 125 ppm. Granite contains about 10 to 50 ppm in the northeastern United States and as much as 500 ppm in the western United States (Mueller Associates, Inc., et al. 1987).

The relative contribution of radon from soil gas to the total radon concentration in a building is proportional to the ratio of foundation area to building volume. The larger the ratio, the more significant the contribution of radon from soil gas. In residences, over 90% of all radon is from the soil. For large, multistory commercial buildings, soil gas is expected to contribute little to the overall radon levels (Godish 1989).

Water - Radon from ground water is found in certain potable water supplies, particularly in wells supplying small public systems where the

storage period is too short to allow for radon decay. Typical radon levels in potable water fall below 2,000 picocuries per liter (pCi/l), but concentrations exceeding 100,000 pCi/l have been found in Maine (Mueller Associates, Inc., et al. 1987). For typical water supplies, 10,000 pCi/l of radon would contribute 1 pCi/l to the indoor air in residences (Mueller Associates, Inc., et al. 1987). In the Pacific Northwest, potable water is considered to be a relatively minor source of radon.

Building Materials - Building materials are a major source of elevated radon concentrations only if their radium content and emanation ratios are very high. Ordinary building materials may be the dominant source of indoor radon in buildings with low to moderate concentrations. This would be especially true in multistory buildings in which the underlying soil contributes relatively little radon per unit volume. Concrete is the strongest radon source; of the components in concrete, sand is the strongest source. Wood is the lowest source of radon (Mueller Associates, Inc., et al. 1987).

2.6.2 Concentrations in Commercial Buildings

Although radon's behavior in commercial and multifamily buildings is poorly understood, the results of a study conducted by Bonneville in the Pacific Northwest showed that radon concentrations are low in a non-representative sample of commercial buildings. Measured radon levels in 39 of the 40 buildings studied were generally low; the geometric mean for all buildings was 0.8 pCi/l. Only 6% of the sample was above the Bonneville mitigation level of 5 pCi/l. The highest building average was 7.4 pCi/l in a Cheney, Washington, office building. The Cheney building has a basement that is partially exposed to bare soil and underground service tunnels with rock block walls and floors. The main air handler fan for the building is located in the basement and draws "fresh" air from the basement and tunnels (Turk et al. 1986).

By comparison, in a study of 250 residences in the Northwest, the average first-floor radon level was 1.2 pCi/l. Only about 4% of the homes experience radon levels above the Bonneville action level guideline of 5 pCi/l (Bonneville 1984).

2.6.3 Environmental Factors

The most significant environmental factors affecting radon concentration in commercial buildings are the weather and soil moisture. The primary mechanism for radon to enter the structure from the soil is through pressure-driven flow (Mueller Associates, Inc., et al. 1987). This flow is the result of a temperature-induced pressure difference across the building envelope and a top-to-bottom pressure difference induced by the wind. These pressure differentials result in a net upward movement of air in the building, with part of the replacement air coming from the building basement/foundation area.

Temperature, pressure, and moisture have been found to affect the rate of radon emanation from building materials. Of these three, moisture content appears to have the most significant effect on increased radon emanation rates (Mueller Associates, Inc., et al. 1987).

2.6.4 Standards, Guidelines, and Regulatory Effects

A number of organizations have recommended guidelines and standards for radon in residences and commercial buildings. Those relevant to commercial buildings are listed in Table 2.14.

TABLE 2.14. Radon Action Levels and Guidelines

Organization	Standard	Comment
National Council on Radiation, Protection and Measurement	8 pCi/l	Recommended action level for general population
ASHRAE and World Health Organization	5.4 pCi/l	Recommended exposure level in commercial buildings and residences
Bonneville	5 pCi/l	Action level for residential weatherization program
EPA	4 pCi/l	Guideline for indoor radon

Source: DOE 1986

2.6.5 Interactions with Energy Conservation Measures

Energy conservation measures that will directly or indirectly affect the indoor concentrations of radon in commercial buildings are described below.

Building Envelope - The impacts of building envelope ECMs on indoor levels of radon are not well understood. Measures that will decrease the infiltration of outdoor air may increase radon concentrations by reducing the rate of fresh-air dilution. However, those same measures may decrease indoor concentrations by blocking the radon entry points and reducing the pressure differences that drive radon entry. Specific ECMs are

- caulking and weatherstripping
- installation of storm doors and windows
- enclosing loading docks with shelters and seals
- installing vestibules
- sealing vertical shafts.

HVAC System - None of the HVAC system ECMs is expected to increase radon concentration. However, if the ECM should result in a lowering of the interior pressure and an increase in the pressure-driven flow into the building, radon entry will increase.

Ventilation - Ventilation system ECMs can result in either an increase or decrease in radon concentration, depending on the measure:

- Automatic reduction of ventilation rates during unoccupied periods will increase radon levels by decreasing the rate of dilution.

- Installing CO_2-controlled ventilation systems will result in decreased levels of radon by increasing the rate of dilution with fresh air.

- Recirculating exhaust air using activated carbon filters that are properly maintained will have a net reducing effect by removal of radon-carrying particulates.

- Installing attic ventilation will increase the transport of radon into the building interior by increasing the top-to-bottom pressure differential.

2.6.6 Specific Mitigation Techniques

The most effective mitigation technique for radon is source control. Incorporation of radon-resistant construction features into building design

before construction will be more cost-effective than remedial actions. Basic preventive measures in new construction include the following (Mueller Associates, Inc., et al. 1987):

- avoidance of high-radium content substances as components of building materials
- attention to site characteristics, such as local geology and soil permeability, which could indicate a potential for high levels of radon-bearing soil gases
- avoidance of sites containing waste materials that are high in radium
- construction techniques with methods that will minimize any high-permeability pathways between the soil and indoors including sealing of radon entry routes
- soil ventilation to draw soil gas away from the building
- crawl space ventilation to exhaust radon before it enters the occupied space of the building
- basement overpressurization to reverse normal pressure gradient to inhibit transport of soil gas into the basement
- air exchange rate increases
- air cleaning using HEPA or electronic filters to remove airborne particulates to which radon products attach.

3.0 VENTILATION

This section presents a general overview of infiltration and mechanical ventilation in commercial buildings and summarizes the results of whole-building air exchange rate measurements.

3.1 CHARACTERIZATION OF VENTILATION

The overall exchange of air in buildings with fresh outside air is the result of the combination of infiltration, natural ventilation, and mechanical ventilation. Even in new buildings, infiltration can be a significant contributor to the total building air exchange rates. This is particularly true in the winter when the driving forces for infiltration are the greatest and the mechanical ventilation systems are operated with a minimum of outside air.

The processes of infiltration, natural ventilation, and mechanical ventilation are described in Sections 3.1.1 and 3.1.2.

3.1.1 Infiltration and Natural Ventilation

Infiltration is the flow of air through cracks, interstices, and unintentional openings in the building envelope. Natural ventilation is under the manual control of building occupants. It occurs through operable windows, doors, skylights, roof ventilators, stacks, and other planned inlet and outlet openings. It can be classified as "controlled" infiltration/exfiltration. The same forces that produce infiltration also drive natural ventilation.

Natural ventilation is more likely to occur during periods of moderate to warm outdoor weather conditions. During these periods, infiltration is at a minimum (low ΔT) and building occupants may open windows and other intentional openings to reduce indoor temperatures or create air motion to increase occupant thermal comfort (Godish 1989). Fortuitously, indoor levels of contaminants may also be reduced by occupants controlling natural ventilation to reduce that "stuffy" feeling of indoor air.

The quantity of air flowing through openings (either unintentional or planned) depends on both the dynamic pressure of the wind and buoyancy forces

resulting from indoor/outdoor temperature differences. The interaction of these forces is summarized below. It is beyond the scope of this report to provide an in-depth discussion of the interaction of these two forces. An excellent treatment of this subject is presented in Godish (1989) and Mueller Associates, Inc., et al. (1987).

The wind effect is due to airflow around a building creating regions in which the static pressure is either greater than (positive) or less than (negative) the pressure inside the building. Simplistically, wind pressures are positive on the windward side of the building and negative on the leeward side. Negative pressures also exist across the top of the building. Positive pressure differentials result in infiltration, and negative pressure differentials result in exfiltration.

The buoyancy force, or stack effect, is a result of the temperature differences between the inside and outside of the building. During the heating season, the warmer inside air is less dense and rises and exits the building near its top. It is replaced by cooler/colder outside air, which flows in near the bottom of the building. The stack effect increases with increasing building height and can be exceptional in tall buildings with vertical passages such as elevator shafts and stairwells.

The degree of air exchange due to infiltration or natural ventilation is dependent on the magnitude of the two driving forces. Infiltration is the greatest during the colder months of the year when indoor/outdoor temperatures are the greatest. During warm weather periods, when natural ventilation is most likely used, the indoor/outdoor temperatures are relatively small, and the stack effect is minimal, the wind effect is the dominant infiltration mechanism. Buildings that rely on natural ventilation to supply their ventilation air are at risk during periods of stagnant conditions.

3.1.2 Mechanical Ventilation

In the past decade, most large commercial buildings have been designed to provide year-round climate control. Because windows are usually sealed, occupant-controlled natural ventilation is restricted. Fresh, outdoor air is available only through a mechanical ventilation system.

Simply defined, mechanical ventilation is the forced movement of air by fans into and out of a building. The primary purpose of the mechanical ventilation system is to provide a healthy and comfortable indoor environment for building occupants. Other purposes include temperature and humidity control, improved thermal comfort, air exchange control, and exhausting smoke, waste heat, and toxic pollutants. Mechanical ventilation systems are designed to provide a range of ventilation rates. Most HVAC systems are designed to operate on a minimum of outside air--averaging 15% to 20% of total airflow. Through intentional control of the dampers, or even failure of the damper controls, the percentage of outside air introduced to the ventilation system can range from 0% to 100% (Godish 1989).

Two of the most commonly used HVAC systems are the constant-air-volume (CAV) system and the variable-air-volume (VAV) system. In the CAV system, supply air is distributed to spaces requiring ventilation and conditioned air through a series of ducts with inlet vents in the ceiling. Return air is drawn from the conditioned space through ceiling outlets into a large return air plenum. Dampers can be operated to control the amount of intake and exhaust air and the percentage of air that is recirculated. Temperature of the occupied space is controlled by regulating the temperature of the supply air. Proper operation of dampers/damper systems is critical for supplying sufficient ventilation air.

Unlike the CAV system, the VAV system regulates temperature in the occupied space by varying the amount of air supplied to the space. This type of system is attractive because it has the potential for significant energy savings. Unfortunately, there are drawbacks to this type of system. First, it is often difficult to ensure that minimum outdoor air ventilation rates for each zone are being satisfied. Second, the system is designed/operated to fully close dampers when temperature setting are reached. Consequently, no ventilation is provided to that space, and complaints of poor indoor air quality frequently arise (Godish 1989).

Ventilation problems experienced in mechanically ventilated building are often the result of poor system operation and/or system maintenance. Typical problems are

- building operated with 100% recirculated air in an attempt to conserve energy
- low ventilation efficiencies so that only a small fraction of the ventilation supply air can thoroughly mix in the occupied space before being exhausted
- system imbalance resulting in some space receiving more ventilation air than others.

3.2 INTERACTION WITH POLLUTANTS

When infiltration and natural ventilation fresh air input rates to a building are restricted, either intentionally or inadvertently, concentrations of indoor air contaminants will increase. Increasing minimum ventilation rates has been one response to this problem. However, a recent study conducted in the Pacific Northwest by Bonneville in 38 commercial buildings found poor correlation between ventilation rates and pollution levels (Turk et al. 1986). Nevertheless, the investigators attributed this poor correlation at least in part to the low pollutant levels observed, which makes the regression techniques unstable. The same conclusion may not be true for other buildings, particularly those with higher levels of contamination. This conclusion is consistent with research done on residential buildings.

The investigators also concluded that buildings with air exchange rates less than the minimum recommended (i.e., ASHRAE Standard 62-1981) do not necessarily have indoor air quality problems. Variations in pollutant source strength (indoor/outdoor), building volumes, and other removal processes can govern pollutant levels.

3.3 STANDARDS

The use of outdoor air for fresh-air ventilation assumes that the levels of contaminants in the ambient air are relatively low and safe for building occupants. ASHRAE Standards 62-1973 and 62-1981 recommend that outdoor air used for ventilation meet ambient air quality standards or be treated so that it does. Unfortunately, this standard is infrequently adhered to (Godish 1989).

The American Society of Heating, Refrigerating, and Air-Conditioning Engineers, Inc., has established minimum mechanical ventilation rates to achieve acceptable indoor air quality, assuming there are no unusual pollutant sources in the building. The first ASHRAE ventilation standard was published in 1973, modified in 1981, and modified again in 1989. ASHRAE Standard 62-1973 specified a minimum ventilation rate for any application of 5 cfm per person and a recommended rate of 20 to 25 cfm per person. The revised standard (ASHRAE 62-1981) specified minimum outside air rates for smoking and nonsmoking areas. The minimum rate for nonsmoking areas was still 5 cfm, but 20 to 35 cfm for smoking areas, depending upon building type.

In 1989, ASHRAE revised the ventilation standard in response to studies showing that a mechanical ventilation rate of 5 cfm was not sufficient to maintain acceptable levels of indoor pollutants. The new standard (ASHRAE 62-1989) increased the minimum outside airflow rate from 5 cfm to 15 cfm per person and combined the smoking and nonsmoking rates into one recommendation. The purpose of this standard 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" (ASHRAE 1989).

The outside airflow rates recommended in Standard 62-1981 and Standard 62-1989 are compared in Table 3.1.

3.4 CHARACTERIZATION OF BUILDING AIR EXCHANGE RATES

A number of studies have been conducted in the past several years to measure the overall air exchange rates in commercial buildings. These studies were conducted in occupied buildings with the HVAC systems in their normal mode of operation. The results of these studies are summarized below.

In a study conducted in the Pacific Northwest, overall average air exchange rate measurements were made in 38 commercial buildings (Turk et al. 1987). The buildings were in two distinctly different climate regions. Ages of the buildings ranged from 0.5 year to 90 years. The overall average air exchange rate was 1.5 ACH with a standard deviation of 0.87 ACH (58% of the mean) with a range of 0.3 ACH to 4.1 ACH. The investigators concluded that no statistically significant relationship existed between ventilation rates and

TABLE 3.1. Recommended Airflow Rates (cfm/person) Contained in ASHRAE Standard 62-1981 and 62-1989

Building Area Type	Standard 62-1981 Nonsmoking	Standard 62-1981 Smoking	Standard 62-1989
Office spaces	5	20	20
Retail stores	5	25	0.02-0.30 cfm/ft^2
Classrooms	5	25	15
Dining rooms	7	35	20
Hotel conference rooms	7	35	20
Office conference rooms	7	35	20
Ballrooms and discos	7	35	25
Spectator areas	7	35	15
Theater auditoriums	7	35	15
Transporting waiting rooms	7	35	15
Hospital patient rooms	7	35	25
Residences	10	10	0.35 ACH[a]
Bars/cocktail lounges	10	50	30
Beauty shops	20	35	25
Smoking lounges	--	--	60

(a) air changes per hour

building height, building age, and number of stories above grade, due in part to the dominating influences of season, air-handling equipment differences, and HVAC system operating policies. Unfortunately, ventilation rates in some of these buildings may have been artificially high because of building operator actions during the monitoring period. In each instance of low ventilation rates (<0.5 ACH), it was found that the outside air dampers were completely closed during the monitoring. In two of the buildings, the dampers were closed for energy conservation measures to reduce the cooling load in the summer. In one building, the system operators were not sure of the damper location or the control mechanism (Turk et al. 1986).

Grot and Persily (1986) measured air infiltration and ventilation rates between 0.28 ACH and 0.70 ACH in eight federal buildings using tracer gas

techniques. The results for each building are shown in Table 3.2. The building minimum air ventilation rate is calculated from the ASHRAE guidelines based on building occupancy levels, building type, and room type. Half of the buildings did not meet the minimum ventilation rates recommended by ASHRAE.

Seven of these eight buildings were new (less than 3 years old at the time of testing) and constructed to the U.S. federal energy guidelines of less than 630 MJ/m^2 per year of off-site energy and less than 1200 MJ/m^2 per year of off-site energy. The building in Fayetteville was 7 years old and built before the energy guidelines were in effect. In general, the investigators concluded that these eight buildings performed better than most existing federal office buildings.

In other studies, ventilation rates in another eight buildings studied by Grot and Persily (1986) ranged from 0.33 ACH to 1.04 ACH. Silberstein and Grot (1985) measured an air exchange rate of 0.9 ACH in a single building.

In the commercial sector, little data exists to characterize air exchange rates in older buildings or to make comparisons between energy-efficient buildings and typical buildings.

TABLE 3.2. Average Ventilation/Infiltration for Eight Federal Buildings

Location	Average ACH	Bldg Minimum ACH
Anchorage	0.28	0.26
Ann Arbor	0.70	0.47
Columbia	0.40	0.62
Fayetteville	0.33	0.32
Huron	0.20	0.13
Norfolk	0.52	0.62
Pittsfield	0.32	0.38
Springfield	0.50	0.55

4.0 MITIGATION

Managing indoor air quality (IAQ) is a process that may begin in the earliest phases of a building's design, or not be attempted until a problem is identified. The earlier in the building's life cycle that IAQ is addressed, the more control options building managers will have to choose from.

4.1 BUILDING COMMISSIONING

As a quality assurance procedure, building commissioning is the process of verifying and documenting the performance of building systems so that they conform with design intent. ASHRAE defines building commissioning as follows:

> Commissioning is the process of achieving, verifying, and documenting that the performance of the HVAC system meets the design intent and owners' functional criteria and operational needs. The process extends through all phases of a project, from concept through occupancy (ASHRAE 1988).

Four key benefits of pursuing building commissioning are as follows:

- Design intent is documented so that building owners, contractors, and operators can calculate and verify energy loads, as well as determine if specified indoor air quality mitigation techniques were properly installed.
- Occupant comfort is ensured, which is important for acceptance of energy-efficient technologies and may reduce the perception of problems with indoor air quality.
- The proper installation and operation of controls and equipment is verified to maximize energy savings and to meet applicable health and safety standards and design intentions.
- A building baseline is established which allows for accurate analysis of performance. Without knowing precisely what equipment is installed, it is difficult to assess performance in terms of expected and actual energy consumption targets.

During the past decade, the thermal environment, which is controlled by the HVAC system, has been the greatest source of occupant complaints in buildings (Trueman 1989a). It has become apparent that operations staff have had increasing difficulty in identifying and correcting HVAC system problems, particularly in new buildings. In almost every case where investigators have

found physical causes for complaints, two factors were at work. Previously undiscovered design deficiencies were identified, and building operators did not understand the proper operations of their building (Trueman 1989a). These factors have also been implicated as contributing to poor indoor air quality (Rask and Lane 1989).

In addition to controlling the thermal and ventilation comfort experienced by building occupants, HVAC systems are typically the single largest consumer of energy in a commercial building. Furthermore, HVAC systems may serve as the sole removal mechanism for indoor air pollutants. Thus, design deficiencies and improper operation have enormous implications for energy efficiency as well as comfort, health, and productivity.

Commissioning could include the inspection of equipment for problems that may lead to poor indoor air quality, and also could include monitoring. If unacceptable indoor air pollutant levels are found during commissioning, recommendations for remediation may include the use of elevated temperatures to encourage vapor offgassing, along with high ventilation rates to flush pollutants to the outdoors (Girman et al. 1989). These steps, referred to as building bake-out, will be most easily implemented if pursued prior to building occupancy.

4.1.1 Costs

Specific costs of the commissioning process will vary by building. However, Levin has suggested that if building commissioning begins in the first stages of a project, there should be no additional costs (ASHRAE 1989b). Trueman (1989b) has calculated the costs and benefits of building commissioning and concluded that the process will result in modest costs, but benefits will outweigh these expenditures two to one. Benefits result from reduced energy costs, corrected deficiencies, and corrected environmental problems. Trueman concludes that commissioning will result in cost increases to the building designer, contractor, and owner. These costs on a typical 100,000-square foot building would amount to a total in the range of $15,000 to $35,000.

4.1.2 Commercial Availability

ASHRAE (1988) has adopted guidelines for building commissioning, and workshops are being held to train engineers and architects in this process. In addition, inspection forms and guidelines from groups other than ASHRAE have been established (for example, the United States Army Corps of Engineers 1988). However, building commissioning is in its infancy and a definitive guide has not yet been developed. A document soon to be published by the National Institute of Standards and Technology may improve this situation.

4.2 SOURCE AVOIDANCE AND CONTROL

Source control refers to methods of control applied at a specific source of pollution, rather than for an entire building or zone. This section addresses nonmechanical methods of source control. Mechanical techniques, such as local ventilation, are discussed in Section 4.3. Techniques for source avoidance and control include removal, substitution, encapsulation, and timing applications for off-hours. Environmental factors such as high humidity or temperatures that contribute to pollutant emissions can also be avoided. These techniques refer primarily to specific sources of pollutants. For additional information, refer to specific pollutants in Section 2.0.

Source avoidance and substitution is likely to work best in the design of new buildings. In existing buildings, the removal of a pollutant source can require renovation, which may be among the most expensive of control techniques. In new buildings, designers have the opportunity to select and integrate mitigation strategies, such as specifying low-emitting materials, conditioning materials before installation, isolating potential sources of pollutants, and using building commissioning activities (see Section 4.1). For example, new building designers may employ the following strategies:

- incorporating isolated rooms for smokers with local exhaust or air treatment
- isolating and incorporating local exhaust in areas with high sources of pollutants, such as kitchens, work rooms, print shops, and laboratories

- using prefilters to reduce the intake of combustion and biogenic particles along with specifying low-emitting building materials
- using hard surfaces in interior designs and minimizing open storage shelving to avoid dust accumulation and to minimize growth areas for microbials
- providing the lowest comfortable air temperature to minimize VOC offgassing
- avoiding high occupant density and providing worker control and privacy.

4.2.1 Costs

Costs will vary by measure. If renovation is required, costs may be high. However, if material substitution is employed as part of planned renovation or new construction, costs may be minimal.

4.2.2 Commercial Availability

Suggestions for evaluating materials and writing specifications have been published (Levin 1989b). However, these procedures are not widespread, and existing guidance is general. Few building materials and products have been tested as potential sources of indoor air pollutants, and a universal grading system has yet to be developed.

4.3 INDOOR AIR QUALITY MANAGEMENT

Sections 4.1 and 4.2 describe engineering techniques to control IAQ. However, many of these techniques require building owners and business managers to commit financial and time resources to design solutions. For example, building commissioning requires engineering expertise, and also requires the building owner to train building operators and give them the time to properly maintain and operate mechanical and structural systems. Source avoidance can also include management decisions in scheduling the application of potential pollutant control.

Other techniques are directly related to management decisions. The following approaches from Levin (1989a) are suggested control measures for buildings with complex cases of sick building syndrome:

- Increase worker control over lighting, ventilation, heating, cooling, and noise.
- Provide flexible work hours where feasible.
- Minimize exposure in stressful positions through job rotation or mandatory rest periods.

Experience from risk communication programs suggests that communication and education efforts may also contribute to pollution control. These efforts can be directed to building operators and custodians, who directly control mechanical systems or may introduce pollutant sources. These efforts also may be important for low- and mid-level managers, as well as other staff. Staff can be trained to recognize potential sources of pollutants and possible symptoms of exposure. Staff can provide input to identify problem areas within buildings and in determining appropriate comfort levels for the building.

4.4 BUILDING DIAGNOSTICS

According to the National Academy of Science (NAS), building diagnostics refers to practices used to assess the current performance and capability of a building and predict its likely performance in the future (NAS 1985). Although many of these techniques can be used for commissioning new buildings, the term often applies to activities in existing buildings.

Efforts are under way to develop standard protocols for conducting building investigations. These protocols are important because diverse disciplines tend to become involved in these investigations. Environmental scientists, chemists, industrial hygienists, architects, mechanical engineers, and public health officials may all become involved in analyzing sick buildings. Thus, it is important that a common language and process be developed to facilitate accuracy and understanding. A four-step process had been identified:

- knowing what to measure
- determining appropriate instrumentation
- interpreting results
- predicting building performance.

The American Society for Testing and Materials (ASTM) has prepared a book documenting several diagnostic techniques (Nagda and Harper 1989). One of these approaches, presented by Woods et al. (1989), outlines a three-phase approach to investigating buildings, which incorporates the four diagnostic principles listed above. The three phases are

- *consultation* - In this phase the objectives and scope of the investigation are defined, a preliminary hypothesis may be formulated, and preliminary recommendations may be presented to the client. Measurements during this phase consist of professional observations by the investigators. A preliminary determination of required subsequent measurements is also made.

- *qualitative diagnostics* - Engineering analysis techniques may be used to validate recommendations or hypothesis. Performance criteria for the various functional areas of the building will be defined. If health problems are suspected, analysis of system performance will be initiated, and measurements will be limited to those required to evaluate the system. If health problems are suspected, immediate medical attention will be recommended for the affected occupants.

- *quantitative diagnostics* - Objective measurements of the physical environment and subjective responses of the occupants will be obtained. If further investigation is needed to test a hypothesis or to validate the recommendations, quantitative measurements of airborne contaminants, bulk samples, and other environmental parameters will be acquired through a systematic format. A thorough quality assurance/quality control program will be implemented.

4.4.1 Costs

References to costs were not found in the literature.

4.4.2 Commercial Availability

National conferences and workshops are conducted on building diagnostics, and professional societies have developed guidelines for implementation. Presenters at these conferences represent public health agencies, engineering firms, mechanical equipment manufacturers, industrial hygienists, and scientists. It appears that services in building diagnoses are becoming more widespread, but are not common in most mechanical engineering and architectural firms.

4.5 MECHANICAL CONTROL OF INDOOR AIR POLLUTANTS

An engineered approach to control of indoor air contaminants often falls into one of two major categories: ventilation and/or air treatment.

4.5.1 Mechanical Ventilation

Mechanical ventilation systems provide a means of reducing the concentrations of all indoor source contaminants by introducing outside air. If improperly designed, however, a ventilation system can create additional problems such as

- introduction of outside air contaminants into the building (e.g., CO from an adjacent parking garage, recirculation of exhausted air from the same or another building into the inlet air grille)
- inadvertent circulation of contaminants generated at one location of the building to other locations in the building
- increased emanation rates of pollutant sources due to feedback effects.

Three different strategies are used to improve indoor air quality through ventilation, including ventilation by dilution, localized exhaust ventilation, and improved room air distribution.

Dilution ventilation reduces indoor air pollutants by introducing a certain amount of outdoor air and exhausting indoor air. The amount of ventilation required to reduce indoor pollutant concentration levels varies. Large amounts of ventilation can result in a substantial rise in energy costs, providing an upper bound on how much ventilation is used. Typically, designers choose the minimum amount of ventilation required by local standards to minimize energy consumption. However, some field measurements suggest that the mechanical ventilation rates in buildings often exceed design rates (Seton, Johnson & Odell, Inc. 1984), a discrepancy that could be the result of either poor construction/commissioning practices or the manual override of ventilation system settings by building operators.

Localized exhaust ventilation is one way to minimize transport of pollutants from an identified source to the general indoor air. Such exhausts

are commonly found in bathrooms, kitchens, laboratories, and smoking areas. These systems can be far more cost-effective than central dilution ventilation.

Ventilation systems perform less than optimally when stratification or nonuniform mixing of air within spaces in the building causes some portion of the supply ventilation air to bypass the occupied space. This "short-circuiting" may occur when supply and return air room diffusers are both located in proximity to each other. To describe the overall effectiveness of a building's ventilation system with respect to contaminant removal, engineers frequently refer to a ventilation efficiency factor. One proposed definition for ventilation efficiency (see ASHRAE 62-1989) is "...The measure of the effectiveness of the ventilation air to provide a contaminant level in the occupied zone of a space divided into the contaminant level produced by a similar amount of ventilation air with perfect mixing in the space..." (McNall 1986). Designing for higher ventilation efficiency appears to be an effective way to improve indoor air quality without significant energy penalties, but is generally practical only in new building design.

4.5.2 Air Treatment

Besides ventilation, air treatment methods are available to mitigate two categories of indoor air pollutants: gaseous and particulate. These methods are commonly used separately or in series in air-handling units, depending on the needs of the building, but also may be applied between a local source and the environment (e.g., recirculating range hoods). Using these methods, the air-handling unit's fan horsepower must be increased because of increased air flow resistance. However, ventilation air quantities needed to provide an equivalent amount of air treatment may then be reduced, lowering building cooling/heating loads, and thus HVAC equipment operating costs. In most commercial buildings, ventilation rates required by local codes are used by designers, because it is more cost-effective to employ one or more of the air treatment devices described below than to increase ventilation rates.

Particulate Removal

Two types of particulate removal systems are predominantly used in commercial building ventilation applications: fibrous filters and electronic air cleaners.

Fibrous Filters. The most common means to remove particulates from the air is through fibrous filtration systems. Typically, filters are mats of fine fibers through which building air passes. Particulates in the air passing through the filter collect on the fibers. Particulate removal systems are rated on their efficiency (i.e., ability to remove particulates), dust-holding capacity, and airflow resistance. Factors affecting the efficiency of fibrous filters include average fiber diameter in the filter, filter thickness, filter packing density/porosity, airflow rate, and particle size.

Several different fibrous filters are commercially available, with a wide range of efficiencies and costs:

- Dry-type panel filters have low efficiencies, and are used typically to stop dust. These filters are applied in most commercial building ventilation systems as either the sole filtration device or as a prefilter for higher efficiency filters.

- Viscous media panel filters have a viscous oily material coated over coarse fibers. Particulates adhere to this material after impacting the fibers. Both viscous and dry panel filters have relatively low pressure drops, and thus impose little energy penalty because of increased fan horsepower requirements. Viscous filters have very low efficiency at removing dust common to indoor air, but are used instead to collect fabric dust and lint (Godish 1989).

- Renewable media filters mechanically supply new filter media whenever the previous filter media becomes excessively clogged. Also called an automatic roll type filter, this mechanism is triggered by a pressure drop sensor across the filter media that has been preset for a maximum allowable pressure drop. Filter media is either dry-type or viscous in these systems.

- Extended surface dry-type filters are considered high-efficiency relative to panel filters, and work through extending filter surface area. This is achieved by either pleating the filter medium, or by creating open "bags" of filter material into which particulates are trapped. By extending the surface in this manner, rather than by simply making the filter thicker, the air pressure drop across the filter is minimized. The most efficient commonly used filter, known

as the high-efficiency particulate air (HEPA), captures in excess of 99.97% of particulates at diameters equal or greater than 0.3 μm (Godish 1989).

To ensure lower fan operating costs and continued high effectiveness, fibrous filters typically must be replaced or reconditioned when they become excessively clogged.

Electronic Air Cleaners. Electrostatic air cleaners remove particulates from an air stream on the principle of electrostatic attraction of opposite charges. Three designs are common: the ionizing plate type, the charged-media non-ionizing type, and the charged-media ionizing type.

In the majority of applications, ionizing plate electronic air cleaners are used. Pressure drop through these air cleaners is very low, and they typically have a fairly high efficiency (80% to 95%). Eventually, as buildup of particulates on the collection plates increases, the effectiveness of the air cleaner decreases. Thus, frequent cleaning of the plates is required to ensure continued high efficiency (Godish 1989).

Charged media non-ionizing air cleaners consist of dielectric filtering medium mats in a field of alternately charged and grounded support members. A strong electrostatic field in the dielectric polarizes particles passing through the air cleaner, causing the particles to be drawn to the mats. Like standard dry-type filter mats, these mats must be periodically replaced or reconditioned.

Charged media ionizing air cleaners are similar to ionizing plate air cleaners except that instead of collection plates, a charged-media filter is used.

Two important environmental concerns are associated with the use of electronic air cleaners (ASHRAE 1988):

- *Space charging* occurs when particulates pass through the ionizer but are not deposited on the collection plates. If sufficient charge develops, these particles are driven to the building's walls. Thus, if the electronic air cleaner is malfunctioning or of low efficiency, inside wall surfaces can quickly become dirtier than if no cleaning device were used. A good design practice when using these systems is to include a fibrous afterfilter to help capture charged particles that escape the collection plates.

- *Ozone production* also may become a problem in electronic air cleaning systems if continuous arcing or brush discharge occurs.

Gaseous Contaminant Removal

Air treatment for the control of the amount of gaseous contaminants in indoor air theoretically may be accomplished by a variety of means, including adsorption, absorption, and catalytic oxidation. However, in commercial building applications, the most widely used method is adsorption and, thus, is the focus of the following discussion.

Adsorption refers to a phenomenon that causes gases, vapors, or liquids contacting a surface to bind to some degree to the surface. Once adsorbed, the gas or vapor molecules remain on the surface as a liquid or semi-liquid.

The adsorbents commonly used for indoor air cleaning come as multiple-sized granules, packed into beds that are configured to minimize resistance to airflow while maximizing dwell time of the air in the adsorption media. These adsorbents commonly have high surface area/volume ratios, and typically comprise of vast labyrinths of submicroscopic pores and minute channels (Godish 1989). Among the most popular adsorbents are activated carbons, activated alumina, silica gel, and surface-active clays. Activated carbon has become the adsorbent of choice in the vast majority of commercial building applications (Turk 1983).

Activated carbons are produced in a variety of sizes and hardnesses (Godish 1989). Hardness is important because a harder carbon helps ensure greater structural integrity for the panels in which it is packed and minimizes the risk that partially crushed granules within the panel would allow contaminants to escape in bypassed air, reducing efficiency of the gas cleaner. Granule size directly impacts the efficiency of an activated carbon gas cleaner. Higher density packings are possible with smaller granules, which improves efficiency, but also results in a greater airflow resistance, affecting the economics of the design being considered.

Activated carbons can vary in their degree of adsorptivity, depending on the characteristics of the application, the carbon, and the contaminants (Godish 1989). For example, the smaller pore diameters in the carbon result

in higher surface areas, which, in turn, promote more adsorptivity. Adsorptive capacity can also vary depending on the contaminant being removed from the airstream. Table 4.1 shows the variation in adsorptive capacities for several different carcinogenic vapors. Elevated airstream humidities (>50%) can reduce activated carbon's adsorption capacity, because carbon's affinity for water vapor increases as humidity increases. However, in the context of air cleaning in commercial building applications, this is a small concern, because the retention rate of water on activated carbon is quite low and, consequently, water is displaced by sorbed gases and vapors, reducing the carbon's adsorptive capacity for water vapor.

TABLE 4.1. Adsorption Capacities of Activated Carbon for 27 Carcinogenic Vapors at 20°C

Vapor	Adsorption capacity, g material/g carbon
Acetamide	0.494
Acrylonitrile	0.357
Benzene	0.409
Carbon tetrachloride	0.741
Chloroform	0.688
bis(chloromethyl)ether	0.608
Chloromethyl methyl ether	0.480
1,2-dibromo-3-chloropropane	0.992
1,1-dibromomethane	0.962
1,2-dibromomethane	1.020
1,2-dichloroethane	0.575
Diepoxy butane (meso)	0.510
1,1-dimethyl hydrazine	0.359
1,2-dimethyl hydrazine	0.375
Dimethyl sulfate	0.615
p-dioxane	0.475
Ethylenimine	0.354
Hydrazine	0.380
Methyl methane sulfonate	0.595
1-naphthylamine	0.585
2-naphthylamine	0.506
N-nitrosodiethylamine	0.442
N-nitrosomethylamine	0.458
B-propiolactone	0.508
Prophylenimine	0.361
Vinyl chloride	0.404
Urethane	0.450

Analogous to particulate air cleaning systems, after being exposed to a contaminant airstream long enough, a carbon air cleaner eventually reaches a saturated state and can no longer adsorb any more contaminants (Godish 1989). After this "breakpoint," the carbon must be replaced.

Activated carbon air cleaner performance can also be enhanced through impregnation of materials on the carbon surface that selectively react with molecules from the gas stream. The products of this reaction are then retained on the carbon surface. This process is called chemisorption. Common activated carbon impregnants and the pollutants they react with are shown in Table 4.2 (Turk 1983).

TABLE 4.2. Activated Carbon Adsorption Impregnations

Impregnant	Pollutant	Action
Bromine	Ethylene; other alkenes	Conversion to dibromide, which remains on carbon
Lead acetate	H_2S	Conversion to PbS
Phosphoric acid	NH_3 amines	Neutralization
Sodium silicate	HF	Conversion to fluorosilicates
Iodine	Mercury	Conversion to HgI_2
Sulfur	Mercury	Conversion to HgS
Sodium sulfite	Formaldehyde	Conversion to addition product
Sodium carbonate or bicarbonate	Acidic vapors	Neutralization
Oxides of Cu, Cr, V, etc.; noble metals (Pd, Pt)	Oxidizable gases, including reduced sulfur compounds such as H_2S and mercaptans	Catalysis of air oxidation

Although performance data is available to indicate adsorption capacity of activated carbon, actual case studies of adsorption/chemisorption air cleaning systems used in commercial building applications are limited. In these cases, judgments of effectiveness are frequently subjective and largely anecdotal (e.g., an occupant assessment of whether an activated carbon air cleaner has removed an objectionable odor in a room or building).

Costs for Air Treatment Systems

Cost estimates for typical in-duct air treatment systems for commercial HVAC applications are described in the *National Mechanical Estimator* (Ottaviano 1987). These estimates include 1987 prices for initial installation and annual operating costs for a typical 10,000 cfm system. The annual operating costs include replacement media, labor charges, and fan power costs that would be incurred because of the pressure drop across the air treatment media. Although not current pricing, these estimates provide a good means of comparing different air treatment systems.

For bag-type filter arrangements with efficiencies ranging from 38% to 40% or 93% to 97%, the corresponding initial costs range from $431 to $1023, and annual operating expenses are $562 and $3129, respectively. Thus, increasing efficiency can be equated with a corresponding steep increase in cost, indicating the importance of carefully analyzing the building's air treatment needs before deciding on a system.

Particulate control using an electrostatic precipitator along with either bag filters or automatic roll filters has higher first costs ($5755) than comparable efficiency system exclusively using fibrous filters ($1053), but lower subsequent annual operating costs ($1222 versus 2402).

Although not directly comparable to particulate removal systems, the activated carbon gas contaminant removal system appears to have fairly high first costs of $7521 (e.g., twice as expensive HEPA systems) and smaller annual operating costs ($1496).

5.0 ENERGY CONSERVATION MEASURES AND INDOOR AIR QUALITY - IMPLICATIONS

The concentration of a pollutant in the indoor environment is dependent on the following factors:

- pollutant source strength
- location of the source in the building or outdoors
- transport and/or mixing of the pollutants within the building
- environmental factors such as temperature, humidity, and synergistic interactions with other pollutants
- the amount and distribution of outside air mixed with the indoor air through infiltration or mechanical ventilation
- removal mechanisms, such as filtration, exhaust ventilation, exfiltration, and air cleaning devices.

The quality of indoor air is dependent on the complex interaction between these factors. To the extent that ECMs may affect a number of these factors, the relationship between ECMs and indoor air quality is difficult to predict. In general, ECMs may affect pollutant concentrations in one of two ways: by introducing a source of pollutants or by changing the rate at which pollutants are removed from (or introduced to) an indoor space.

Potential sources of indoor VOCs from energy conservation measures include caulking compounds and insulation. Of the two potential sources discussed, caulking emits the highest rates of VOCs, but these are likely to be quickly dissipated. Insulation materials emit pollutants at a lower rate, but have the potential of emitting them over a longer time period. Emissions from fibrous insulation may be related to how moist the material is (van der Wal et al. 1987).

The second way in which energy conservation measures may affect indoor VOC levels is by changing the rate at which pollutants are removed from a space. The most common removal mechanism involves the exchange of indoor and outdoor air in ventilation systems. If conservation measures involve reducing the quantities of outside air without including air-cleaning equipment, indoor levels of pollutants are likely to increase. On the other hand, if conservation measures such as economizers are employed, increasing quantities of

outside air, indoor pollutant levels are likely to decrease. A more thorough discussion of ventilation is contained in Section 3 of this report.

In existing buildings, energy conservation can affect the sources and removal rates of indoor pollutants through inspections and improved maintenance of the building structure and the HVAC system. Perhaps the most direct positive effects will be on microbial growth in the HVAC system and on building surfaces. For example, caulking around windows may eliminate the entry of wind driven rain, which fosters the growth of molds and fungi (Rask and Lane 1989). Inspections may also discover microbial growth areas in ductwork near cooling coils, or design deficiencies such as the placement of air intakes near sources of pollutants such as garbage storage areas or parking garages (Rask and Lane 1989; Morey 1988).

However, if building inspections result in reductions in ventilation rates, there is likely to be a negative effect on indoor air quality. A field study suggests that ventilation rates often exceed ASHRAE Standard 62-1981. Seton, Johnson & Odell, Inc. (1984) conclude that nominal ventilation rates based on actual occupancy are significantly higher that the design rates listed in Standard 62-1981. Turk et al. (1987) found that in a sample of 40 buildings, on average, ventilation rates ranged from 2 to 8 times the rates recommended for smoking areas in Standard 62-1981. The ventilation rates contained in Standard 62-1981 for smoking areas (as opposed to the ventilation rates listed for nonsmoking areas) are greater than the single ventilation rates listed in ASHRAE Standard 62-1989. Thus, Turk's findings suggest that in existing buildings, ventilation rates exceed both the new ASHRAE Standard 62-1989 and the old ASHRAE Standard 62-1981. If the ventilation rates are reduced to match either of the standards, there is likely to be a negative effect on indoor pollution concentrations.

Table 5.1 summarizes the potential impacts of ECMs on indoor air quality. For this discussion, the ECMs will have either a direct or an indirect impact on the indoor air quality. A direct impact is one that directly increases (decreases) the source strength by increasing (decreasing) the amount of source material or its emanation rate. An indirect impact is

TABLE 5.1. List of Candidate Energy Conservation Measures and Associated IAQ Impacts

Energy Conservation Measure	RSP Fibers	RSP Particles	Biogenic	Radon	Combustion Gases	VOCs
Building Envelope						
Install wall, ceiling, roof, floor, foundation and slab insulation	D+	nc	nc	nc	nc	D+
Reduce heat/cool loads from infiltration by caulking and weatherstripping	I+	I±	I±	I+	I±	D+ I+
Install storm windows/doors	I±	I±	I-	I+	I±	I+
Enclose loading docks with shelters and seals	I±	I±	I±	I+	I±	I+
Install vestibules to reduce infiltration/exfiltration	I±	I±	I±	I+	I±	I+
Seal vertical shafts to reduce in/exfiltration	I±	I±	I±	I+	I±	I+
Heating/Air Conditioning						
Install automatic condenser cleaning	u	u	D-	u	u	D+
Replace air-cooled condenser with cooling tower	nc	nc	D+	nc	nc	nc
Install spot cooling	nc	nc	D+	nc	nc	nc
Install earth cooling tubes	nc	nc	D+	nc	nc	nc

TABLE 5.1. (contd)

Energy Conservation Measure	RSP Fibers	RSP Particles	Biogenic	Radon	Combustion Gases	VOCs
Install roof spray systems	nc	nc	D+	nc	nc	nc
Install economizer (air side)	u	u	u	u	u	I-
Install warm-up cycle controls/optimum start	u	u	u	u	u	I-
Install automatic setback/ setup thermostats	u	u	u	u	u	I+
Insulate ducts	D+	nc	I-	nc	nc	D+
Ventilation						
Install CO_2-controlled ventilation	u	u	u	u	I-	nc
Install CO-controlled covered parking ventilation	u	u	u	u	D-	nc
Automatically reduce ventilation during unoccupied periods	I±	I±	I±	I+	I±	I+
Reduce minimum outside air	u	u	u	u	u	I+
Recirculate exhaust air using activated carbon filters	D+	I-	I-	I-	I-	I-
Install vortex hoods for restaurants	nc	I-	nc	nc	I-	I-

TABLE 5.1. (contd)

Energy Conservation Measure	RSP Fibers	RSP Particles	Biogenic	Radon	Combustion Gases	VOCs
Employ evaporative cooling of outdoor air	nc	nc	D+	nc	nc	nc
Employ desiccant dehumidification	u	u	u	u	u	nc
Reduce energy consumption for fans by reducing air flow rates and resistance to air flow	nc	nc	nc	nc	nc	nc
Install high efficiency fans with larger ductwork	u	u	u	u	u	I-
Install dual speed fans	u	u	u	u	u	I-
Install attic ventilation	nc	nc	nc	I+	nc	I-
Install low leakage dampers	u	u	u	u	u	I-
Install ceiling fans	u	u	u	u	u	nc
Install outside air reset control	u	u	u	u	u	nc

KEY D = direct effect
I = indirect effect
+ = increase pollutant levels
- = decrease pollutant levels
± = either increase or decrease depending on whether indoor or outdoor source
nc = no change
u = unsure

one that modifies or in some way increases (decreases) the pollutant concentration in the indoor environment through increasing (decreasing) the dilution rate or removal rate. Materials used in the ECM itself may also be a direct source of an indoor pollutant. These are indicated in Table 5.1 by the D+ symbol. They fall into two broad categories--those that increase amounts of thermal insulation material and those that modify the HVAC system and increase the available growth media for biogenic material. For instance, adding thermal insulation to the HVAC system ducts will increase the amount of fiber material in the building and increase the potential for release of RSP fibers to the air, distributed by the HVAC system.

6.0 REFERENCES

ASHRAE. 1972. *ASHRAE Standard 62-1972 - Ventilation for Acceptable Indoor Air Quality*. American Society of Heating, Refrigerating, and Air-Conditioning Engineers, Inc., Atlanta, Georgia.

ASHRAE. 1981. *ASHRAE Standard 62-1981 - Ventilation for Acceptable Indoor Air Quality*. American Society of Heating, Refrigerating, and Air-Conditioning Engineers, Inc., Atlanta, Georgia.

ASHRAE. 1988. *ASHRAE Guideline - HVAC Systems Commissioning*. American Society of Heating, Refrigerating, and Air-Conditioning Engineers, Inc., Atlanta, Georgia.

ASHRAE. 1989a. *ASHRAE Standard 62-1989 - Ventilation for Acceptable Indoor Air Quality*. American Society of Heating, Refrigerating, and Air-Conditioning Engineers, Inc., Atlanta, Georgia.

ASHRAE. 1989b. "Excerpts from Summary Workshop." *The Human Equation: Health and Comfort*, Proceedings of the ASHRAE/SOEG Conference IAQ 89, April 12-20, 1989, San Diego, California. American Society of Heating, Refrigerating, and Air-Conditioning Engineers, Inc., Atlanta, Georgia.

Baechler, M.C., H. Ozkaynak, J.D. Spengler, L.A. Wallace, and W.C. Nelson. 1989. Assessing Indoor Exposure to Volatile Organic Compounds Released from Paint Using the NASA Data Base." In *Proceedings of the Annual Meeting of the Air and Waste Management Association*, Anaheim, California, June 20-22. Air and Waste Management Association, Pittsburgh, Pennsylvania.

Berglund, B., I. Johansson, and T. Lindvall. 1987. "Volatile Organic Compounds from Building Materials in a Simulated Chamber Study." In *Indoor Air '87: Proceedings of the 4th International Conference on Indoor Air Quality and Climate*. Institute for Water, Soil and Air Hygiene, Berlin.

Bonneville Power Administration. 1982. *Environmental Assessment of Energy Conservation Opportunities in Commercial-Sector Facilities in the Pacific Northwest*. DOE/EA-0187, Portland, Oregon.

Bonneville Power Administration. 1984. *Final Environmental Impact Statement: The Expanded Residential Weatherization Program*. DOE/EIS-0095F, Portland, Oregon.

Bonneville Power Administration. 1988. *Final Environmental Impact Statement on New Energy-Efficient Homes Programs: Assessing Indooor Air Quality Options*. DOE/EIS-0127F, Portland, Oregon.

Borrazzo, J.E., J.F. Osborn, R.C. Fortmann, and C.I. Davidson. 1985. *Airborne Concentrations of CO, NO_x, and Particulates in a Modern Townhouse--Model Predictions vs. Experimental Results*. Departments of Civil Engineering, Engineering & Public Policy, and Biomedical Engineering, Carnegie-Mellon University, Pittsburgh, Pennsylvania.

Brundage, J.F., R.M Scott, W.M. Lednar, D.W. Smith, and R.N. Miller. 1988. "Building-Associated Risk of Febrile Acute Respiratory Diseases in Army Trainees." *Journal of the American Medical Association* 259(14):2108-2112.

Burge, H.A. 1985. "Indoor Sources for Airborne Microbes," *Indoor Air and Human Health*, Proceedings of the Seventh Life Sciences Symposium, Knoxville, Tennessee, October 29-31, 1984, Garnage and Kaye, eds., pp. 139-148.

Burge, P.S. 1990. "Building Sickness - A Medical Approach to the Causes." *In Indoor Air 90: Proceedings of the Fifth International Conference on Indoor Air Quality and Climate*. Canada Mortgage and Housing Corporation, Toronto.

Carey, J.M., M. Hager, P. King, and S. Zuckerman. January 7, 1985. "Beware Sick-Building Syndrome." *Newsweek*.

Crouse W.E., M.S. Ireland, J.M. Johnson, R.M. Striegel, Jr., C.S. Williard, R.M. DePinto, G.B. Oldaker III, and R.L. McBride. 1988. "Results from a Survey of Environmental Tobacco Smoke (ETS) in Restaurants." In *Transactions of an International Specialty Conference: Combustion Processes and the Quality of the Indoor Environment*, ed. J.P. Harper, pp. 214-219. September 1988, Niagara Falls, New York.

Fanger, P.O. 1989. "The New Comfort Equation for Indoor Air Quality." In The Human Equation: Health and Comfort, Proceedings of the ASHRAE/SEOG Conference IAQ 89, April 12-20, 1989, San Diego, California. American Society of Heating, Refrigerating, and Air-Conditioning Engineers, Inc., Atlanta, Georgia.

Fanger, P.O. 1990. "New Principles for a Future Ventilation Standard." *In Indoor Air 90: Proceedings of the Fifth International Conference on Indoor Air Quality and Climate*. Canada Mortgage and Housing Corporation, Toronto.

Flachsbart, P.G, and D. E. Brown. 1985. "Merchant Exposure to CO from Motor Vehicle Exhaust at Honolulu's Ala Moana Shopping Center." In *Proceedings of the 78th Annual Meeting of the Air Pollution Control Association*, June 16-21, 1985, Detroit, Michigan. Air Pollution Control Association, Pittsburgh, Pennsylvania.

Gamboa, R.R., B.P. Gallagher, and K.R. Mathews. 1988. "Data on Glass Fiber Contribution to the Supply Airstream from Fiberglas Duct Liner and Fiberglas Duct Board." In *IAQ 88: Engineering Solutions to Indoor Air Problems*, pp. 25-33. American Society of Heating, Refrigerating, and Air-Conditioning Engineers, Inc., Atlanta, Georgia.

Girman J., L. Alvantis, and G. Kulasingam. 1987. "Bake Out of an Office Building." In *Indoor Air "87: Proceedings of the 4th International Conference on Indoor Air Quality and Climate.* Institute for Water, Soil and Air Hygiene, Berlin.

Girman, J.R., L. Alevantis, M. Petreas, and L. Webber. 1989. "The Bake-Out of an Office Building: A Case Study." *Environment International* 15:449-453.

Godish, T. 1989. *Indoor Air Pollution Control*. Lewis Publishers, Inc., Chelsea, Michigan.

Grot, R.A., and A.K. Persily. 1986. "Measured Air Infiltration and Ventilation Rates in Eight Large Office Buildings." In *Measured Air Leakage of Buildings, ASTM STP 904*, eds. H.R. Trechel and P.L. Lagus, pp. 151-183. American Society for Testing and Materials, Philadelphia.

Hawthorne, A.R., and T.G. Mathews. 1985. "Formaldehyde: An Important Indoor Pollutant." In *Proceedings: Indoor Air Quality Seminar--Implications for Electric Utitlity Conservation Programs*, EPRI EA/EM-3824, pp. 8.1-8.7. Electric Power Research Institute, Palo Alto, California.

Jungers, R.H., and L.S. Sheldon. 1987. "Characterization of Volatile Organic Chemicals in Public Access Buildings." *In Indoor Air '87: Proceedings of the 4th International Conference on Indoor Air Quality and Climate*. Institute for Water, Soil and Air Hygiene, Berlin.

Kandarjian, L. 1988. "Federal Policy Options for Indoor Air Pollution from Combustion Appliances." In *Transactions of an International Specialty Conference: Combustion Processes and the Quality of the Indoor Environment*, ed. J.P. Harper, pp. 310-332. September 1988, Niagara Falls, New York.

Levin H. 1989a. "Sick Building Syndrome: Review and Exploration of Causation Hpotheses and Control Methods." In *The Human Equation: Health and Comfort*, Proceedings of the ASHRAE/SOEG Conference IAQ 89, April 12-20, 1989, San Diego, California. American Society of Heating, Refrigerating, and Air-Conditioning Engineers, Inc., Atlanta, Georgia.

Levin H. ed. 1989b. "Specifying Interior Materials." *Indoor Air Quality Update* 2(4):5-11.

McNall, P.E. 1986. "Strategies: Today and Tomorrow." *ASHRAE Journal* 28(7):37-40.

McNall, P.E. 1988. "Control Technology and IAQ Problems." In *Engineering Solutions to Indoor Air Problems*, Proceedings of the ASHRAE Conference IAQ 88, April 11-13, 1988, Atlanta Georgia. American Society of Heating, Refrigerating, and Air-Conditioning Engineers, Inc., Atlanta, Georgia.

Melius, J., K. Wallingford, J. Carpenter, and R. Keenslyside. 1984. "Indoor Air Quality: The NIOSH Experience." *Am Conf Ind Hyg Report* 10:3-7.

Miele, P.F. 1989. "Formaldehyde Emissions from Bonded Fiberglass Insulation Products." In *The Human Equation: Health and Comfort*, Proceedings of the ASHRAE/SOEG Conference IAQ 89, April 12-20, 1989, San Diego, California. American Society of Heating, Refrigerating, and Air-Conditioning Engineers, Inc., Atlanta, Georgia.

Miksch, R.R., C.D. Hollowell, and H.E. Schmidt. 1982. *Trace Organic Chemical Contaminants in Office Spaces*. LBL-12561, Lawrence Berkeley Laboratory, Berkeley, California.

Molhave, L. 1982. "Indoor Air Pollution Due To Organic Gases and Vapours of Solvents in Building Materials." *Environment International* 8:117-127.

Molhave, L. 1985. "Volatile Organic Compounds as Indoor Air Pollutants." In *Indoor Air and Human Health, Proceedings of the Seventh Life Sciences Symposium*, eds. R.B. Gammage and S.V. Kaye, pp. 403-414. October 29-31, 1984, Knoxville, Tennessee. Lewis Publishers, Inc, Chelsea, Michigan.

Molhave, L., B. Bach, and O.F. Pedersen. 1985. "Human Reactions During Controlled Exposures to Low Concentrations of Organic Gases and Vapours Known as Normal Indoor Air Pollutants." *In Indoor Air. Vol. 3: Sensory and Hyperactivity Reactions to Sick Buildings - Proceedings of the International Conference (3rd) on Indoor Air Quality and Climate*, pp. 431-436. Swedish Council for Building Research, Stockholm.

Molhave, L. 1990. "Volatile Organic Compounds, Indoor Air Quality and Health." *In Indoor Air 90: Proceedings of the Fifth International Conference on Indoor Air Quality and Climate*. Canada Mortgage and Housing Corporation, Toronto.

Morey, P.R. 1988. "Microorganisms in Buildings and HVAC Systems: A Summary of 21 Environmental Studies." In *Engineering Solutions to Indoor Air Problems*, Proceedings of the ASHRAE Conference IAQ 88, April 11-13, 1988, Atlanta Georgia. American Society of Heating, Refrigerating, and Air-Conditioning Engineers, Inc., Atlanta, Georgia.

Morey, P.R., and B.A. Jenkins. 1989. "What are Typical Concentrations of Fungi, Total Volatile Organic Compounds, and Nitrogen Dioxide in an Office Environment?" In *The Human Equation: Health and Comfort*, Proceedings of the ASHRAE/SOEG Conference IAQ 89, April 12-20, 1989, San Diego, California. American Society of Heating, Refrigerating, and Air-Conditioning Engineers, Inc., Atlanta, Georgia.

Mueller Associates, Inc., Argonne National Laboratory, and Brookhaven National Laboratory. 1987. *Indoor Air Quality Environmental Information Handbook: Building System Characteristics*. DOE/EV/10450-H1, U.S. Department of Energy, Washington, D.C.

Mueller Associates, Inc., SYSCON Corporation, and Brookhaven National Laboratory. 1985. *Indoor Air Quality Environmental Information Handbook: Combustion Sources*. DOE/EV/10450-1, U.S. Department of Energy, Washington, D.C.

Nagda N.L., and J.P. Harper, eds. 1989. *Design and Protocol for Monitoring Indoor Air Quality*. The American Society for Testing and Materials, Philadelphia.

National Academy of Science (NAS). 1985. *Building Diagnostics: A Conceptual Framework*. National Academy Press, Washington, D.C.

Ottaviano, V.B. 1987. *National Mechanical Estimator*. Ottaviano Technical Services, Inc., and Fairmont Press, Atlanta, Georgia.

Ozkaynak, H., and P.B. Ryan. 1987. "Sources and Emission Rates of Organic Chemical Vapors in Homes and Buildings." *In Indoor Air '87: Proceedings of the 4th International Conference on Indoor Air Quality and Climate*. Institute for Water, Soil and Air Hygiene, Berlin.

Rask, D.R., and C.A. Lane. 1989. "Resolution of the Sick Building Syndrome: Part II, Maintenance." In *The Human Equation: Health and Comfort*, Proceedings of the ASHRAE/SOEG Conference IAQ 89, April 12-20, 1989, San Diego, California. American Society of Heating, Refrigerating, and Air-Conditioning Engineers, Inc., Atlanta, Georgia.

Seifert, B, D. Ullrich, and R. Nagel. 1989. "Volatile Organic Compounds from Carpeting" in *Man and His Ecosystem; Proceedings of the 8th World Clean Air Congress*, 11-15 September 1989, The Hague. Elsevier Science Publishers, Amsterdam.

Seton, Johnson & Odell, Inc. 1984. *Ventilation in Commercial Buildings*. Prepared for the Office of Conservation, Bonneville Power Administration, Portland, Oregon.

Sexton, K., J.D. Spengler, and R.D. Treitman. 1984. "Effects of Residential Wood Combustion on Indoor Air Quality: A Case Study in Waterbury, Vermont." *Atmospheric Environment*.

Sheldon, L.S., R.W. Handy, T.D. Hartwell, R.W. Whitmore, H.S. Zelon, and E.D. Pellizzari. 1988a. *Indoor Air Quality in Public Buildings*, Vol 1. EPA/600/S6-88/009a. U.S. Environmental Protection Agency, Washington, D.C.

Sheldon, L., H. Zelon, J. Sickles, C. Eaton and T. Hartwell. 1988b. *Indoor Air Quality in Public Buildings*, Vol. 2. U.S. Environmental Protection Agency, Washington, D.C.

Silberstein, S., and R.A. Grot. 1985. "Air Exchange Rates Measurements of the National Archive Building." *ASHRAE Transactions* 91(2A).

Skov, P., and O. Valbjorn. 1987. "The Sick Building Syndrome in the Office Environment: The Danish Town Hall Study, Indoor Air '87." In *Proceedings of the 4th International Conference on Indooor Air Quality and Climate*, Berlin.

Spengler, J.D., and K. Sexton. 1983. "Indoor Air Pollution: A Public Health Perspective." *Science* 221(4605):9-17.

Spengler, J.D. and M.A. Cohen, 1985. "Emissions from Indoor Combustion Sources". *Indoor Air and Human Health*, Proceedings of the Seventh Life Sciences Symposium, Knoxville, TN, October 29-31, 1984, Garnage and Kaye, eds., pp. 261-278.

Sterling, T.D., C.W. Collett, and J.A. Ross. 1988. "Levels of Environmental Tobacco Smoking Under Different Conditions of Ventilation and Smoking Regulations." In *Transactions of an International Specialty Conference: Combustion Processes and the Quality of the Indoor Environment*, ed. J.P. Harper, pp. 223-235. September 1988, Niagara Falls, New York.

Sterling, E.M., and T.D. Sterling. 1984. "Baseline Data: Health and Comfort in Modern Office Buildings." *In Proceedings of the 5th Air Infiltration Center Conference: The Implementation and Effectiveness of Air Infiltration Standards in Buildings*. International Energy Agency, The Air Infiltration Center, Berkshire, England.

Tichenor, B.A., and M.A. Mason. 1988. "Organic Emissions from Consumer Products and Building Materials to the Indoor Environment." *JAPCA* 38:264-268.

Tichenor, B.A., L.E. Sparks, M.D. Jackson, Z. Guo, and S.A. Rasor. 1990. "The Effect of Wood Finishing Products on Indoor Air Quality." Presented at *Measurement of Toxic and Related Air Pollutants*, Raleigh, North Carolina, 30 April - 4 May 1990. Sponsored by the U.S. Environmental Protection Agency and the Air and Waste Management Association.

Trueman, C.S. 1989a. Untitled presentation to *Dimension '89 - A Seminar for the Building Design Professiona* March 15-17, 1989.

Trueman, C.S. 1989b. "Commissioning: An Owner's Approach for Effective Operations." *ASHRAE Transactions 1989*. American Society of Heating, Refrigerating, and Air-Conditioning Engineers, Inc., Atlanta, Georgia.

Turk, A. 1983. "Gaseous Air Cleaning Can Help Maintain Tolerable Indoor Air Quality Limits." ASHRAE Journal, pp. 35-37.

Turk, B.H., J.T. Brown, K. Geisling-Sobotka, D.A. Froehlich, D.T. Grimsrud, J. Harrison, and K.L. Revzan. 1986. "Indoor Air Quality Measurements in 38 Pacific Northwest Commercial Buildings." In *Proceedings of the 79th Annual Meeting of the Air Pollution Control Association*, Minneapolis, Minnesota. Air Pollution Control Association, Pittsburgh, Pennsylvania.

Turk, B.H, J.T. Brown, K. Geisling-Sobotko, D.A. Froehlich, G.T. Grimsrud, J. Harrison, J.F. Koonce, R.J. Prill, and K.L. Revzan. 1987. *Indoor Air Quality and Ventilation Measurements in 38 Pacific Northwest Commercial Buildings.* Bonneville Power Administration, Portland, Oregon.

Turner, S. 1988. "Environmental Tobacco Smoke and Smoking Policy." In *Transactions of an International Specialty Conference: Combustion Processes and the Quality of the Indoor Environment*, ed. J.P. Harper, pp. 236-247.

U.S. Army Corps of Engineers (USACOE). 1988. Acceptance Test Procedure for Air Supply and Distribution Systems.

U.S. Environmental Protection Agency (EPA). 1988. "Indoor Air Facts No. 4: Sick Buildings." Washington, D.C.

U.S. Department of Energy (DOE). 1986. *Environmental Assessment in Support of Proposed Interim Energy Conservation Standards for New Commercial and Multifamily Highrise Residential Buildings.* DOE/CE-0166, Washington, D.C.

Valbjorn, O., and P. Skov. 1987. "Influence of Indoor Climate on the Sick Building Syndrome, Indoor Air." In *Proceedings of the 4th International Conference on Indoor Air Quality and Climate.* Institute for Water, Soil and Air Hygiene, Berlin.

van der Wal, J.F., A.M.M. Moons, and R. Steenlage. 1987. "Thermal Insulation as a Source of Air Pollution." In *Indoor Air '87: Proceedings of the 4th International Conference on Indoor Air Quality and Climate.* Institute for Water, Soil and Air Hygiene, Berlin.

Wallace, L. 1985. "Part Five: Overview." In *Indoor Air and Human Health, Proceedings of the Seventh Life Sciences Symposium*, eds. R.B. Gammage and S.V. Kaye, pp. 331-333. October 29-31, 1984, Knoxville, Tennessee. Lewis Publishers, Inc, Chelsea, Michigan.

Wallace, L. 1987. "Emissions of Volatile Organic Compounds from Building Materials and Consumer Products." In *Indoor Air '87: Proceedings of the 4th International Conference on Indoor Air Quality and Climate.* Institute for Water, Soil and Air Hygiene, Berlin.

Wallace L., R. Jungers, L. Sheldon, and E. Pellizzari. 1987. "Volatile Organic Chemicals in 10 Public-Access Buildings." In *Indoor Air '87: Proceedings of the 4th International Conference on Indoor Air Quality and Climate.* Institute for Water, Soil and Air Hygiene, Berlin.

White, J.B., J.C. Reaves, P.C. Reist, and L.S. Mann. 1988. "A Data Base on the Sources of Air Pollution Emissions." In *Engineering Solutions to Indoor Air Problems*, Proceedings of the ASHRAE Conference IAQ 88, April 11-13, 1988, Atlanta Georgia. American Society of Heating, Refrigerating, and Air-Conditioning Engineers, Inc., Atlanta, Georgia.

Woods, J.E., P.R. Morey, and D.R. Rask. 1989. "Indoor Air Quality Diagnostics: Qualitative and Quantitative Procedures to Improve Environmental Conditions." In *Design and Protocol for Monitoring Indoor Air Quality*, eds. N.L. Nagda and J.P. Harper. The American Society for Testing and Materials, Philadelphia.

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