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Indoor Air Quality Environmental Information Handbook: Combustion Sources 1989 Update

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FOREWORD

The types and concentrations of air contaminants found in the indoor residential environment depend on the characteristics and use of the equipment/materials in the environment as well as on the nature of the building system. Designers, builders, and homeowners make decisions about building structure design, construction, and operation, household furnishings and activities, appliance types and operation, and home sites that ultimately affect the kinds and potential levels of indoor air pollutants. Consumer concerns about energy costs have contributed to major changes in the design and construction of new residences and to the retrofitting of existing residences to reduce the exchange of air between the indoors and outdoors. Many trade-offs are involved when the potential health risks posed by elevated pollutant levels and the selection of mitigating measures are considered.

The U.S. Department of Energy has a long-standing interest in investigating the impact of energy conservation measures on residential indoor air quality. The Office of Environmental Analysis has prepared this handbook in an effort to bring together currently available information on residential combustion sources that influence the indoor atmosphere. This is the third in a series of handbooks on indoor air quality designed to enhance understanding of the current state of knowledge regarding residential indoor air quality for technical persons as well as non-technical readers. The handbook provides the reader with a review and reference source on common combustion-generated indoor air pollutants (sources, typical concentrations, health effects, and standards) and available methods for controlling these pollutants.

We recognize that the information presented here is subject to change as new information becomes available from on-going research on indoor air quality. We, therefore, welcome your comments, corrections, or suggestions for improving future editions, and encourage you to send them to me at the U.S. Department of Energy, 1000 Independence Avenue, S.W., Washington, D.C. 20585.

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In addition, draft review comments for the 1990 revision were received from: Jonathan M. Samet, M.D. (University of New Mexico), Gregory W. Traynor and colleagues (Lawrence Berkeley Laboratory), Irwin H. Billick (Gas Research Institute), Michael D. Rowe (Brookhaven National Laboratory), Esther Kweller (U.S. Department of Energy), Thomas A. King (International Development and Energy Associates, Inc.), and John Borrazzo (Carnegie Mellon University).

Special thanks are extended to Mrs. Ann Gunther and Ms. Colleen Gibbs for their perseverance in completing the manuscript with a high level of quality.

ABSTRACT

This environmental information handbook was prepared to assist both the non-technical reader (i.e., homeowner) and technical persons (such as researchers, policy analysts, and builders/designers) in understanding the current state of knowledge regarding combustion sources of indoor air pollution. Quantitative and descriptive data addressing the emissions, indoor concentrations, factors influencing indoor concentrations, and health effects of combustion-generated pollutants are provided. In addition, a review of the models, controls, and standards applicable to indoor air pollution from combustion sources is presented. The emphasis is on the residential environment.

The data presented here have been compiled from government and privately-funded research results, conference proceedings, technical journals, and recent publications. It is intended to provide the technical reader with a comprehensive overview and reference source on the major indoor air quality aspects relating to indoor combustion activities, including tobacco smoking. In addition, techniques for determining potential concentrations of pollutants in residential settings are presented. This information can be used by homeowners/consumers to evaluate the trade-offs involved in potential mitigating measures and to make better decisions regarding combustion sources of indoor pollution within their homes.

This handbook is an update of a 1985 study documenting the state of knowledge of combustion-generated pollutants in the indoor environment.

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ABBREVIATIONS, ACRONYMS, AND SYMBOLS

ach, ACH	air changes per hour
ANSI	American National Standards Institute
APCA	Air Pollution Control Association (now Air and Waste Management Association)
ASHRAE	American Society of Heating, Refrigerating and Air Conditioning Engineers
avg	average
BaP	benzo(a)pyrene
BNL	Brookhaven National Laboratory
BPA	Bonneville Power Administration
Btu, BTU	British thermal unit
°C	degrees Celsius
CEQ	Council on Environmental Quality
cfh	cubic feet per hour
cfm	cubic feet per minute
CFR	Code of Federal Regulations
CG	chromatographic
CH ₄	methane
cm	centimeter
CO	carbon monoxide
CO ₂	carbon dioxide
CO _x	carbon oxides
COHb	carboxyhemoglobin
CPSC	Consumer Product Safety Commission
DOE	U.S. Department of Energy
EPA	U.S. Environmental Protection Agency

°F	degrees Fahrenheit
FHA	Federal Housing Administration
ft, FT	feet
g	gram
GI	gastrointestinal
GIOAP	Geomet Indoor-Outdoor Air Pollution
GRI	Gas Research Institute
hr	hour
HCHO	formaldehyde
HUD	U.S. Department of Housing and Urban Development
IAQ	indoor air quality
IGT	Institute of Gas Technology
in	inch
I/O	indoor/outdoor
IITRI	Illinois Institute of Technology Research Institute
J	Joule
l, L	liter
LBL	Lawrence Berkeley Laboratory
lb	pounds
m	meter
max	maximum
mg	milligram
min	minute
ml, ML	milliliter
mm	millimeter
MPS	Minimum Property Standards

MRP	mass respirable particulates
n	integer
NAAQS	National Ambient Air Quality Standard
NAS	National Academy of Sciences
nCi	nanocuries
ng	nanogram
NO	nitric oxide
NO ₂	nitrogen dioxide
NO _x	nitrogen oxides
NRC	National Research Council
O ₂	oxygen
O ₃	ozone
O(^{3p})	elementary reaction with oxygen atom
ORNL	Oak Ridge National Laboratory
OSHA	Occupational Safety and Health Administration
Pa	Pascal
PAH	polycyclic aromatic hydrocarbons
PAN	peroxyacetylnitrates
ppb	parts per billion
ppm	parts per million
r	ratio
RSP	respirable suspended particles
RTP	Research Triangle Park, North Carolina
s, sec	second
scf	standard cubic feet
SD	standard deviation

SF ₆	sulfur hexafluoride
SO ₂	sulfur dioxide
So Cal Gas Co.	Southern California Gas Company
t	time
THC	total hydrocarbons
TSP	total suspended particles
TVA	Tennessee Valley Authority
UVGSH	unvented gas space heater
V	volume
wk	week
yr	year
τ	time increment
μg	microgram
μm	micrometer

CONVERSION FACTORS FOR
POLLUTANT CONCENTRATIONS

Nitrogen Oxide	1 ppm = 1.2 mg/m ³
Nitrogen Dioxide	1 ppm = 1.8 mg/m ³
Carbon Monoxide	1 ppm = 1.15 mg/m ³
Carbon Dioxide	1 ppm = 1.8 mg/m ³
Sulfur Dioxide	1 ppm = 2.64 mg/m ³
Formaldehyde	1 ppm = 1.23 mg/m ³

Section 1

INTRODUCTION AND SUMMARY

The quality of indoor air--in the home, workplace, or a public facility--has a strong influence on the overall health effects attributable to air pollution. Information suggests that potentially harmful concentrations of some airborne contaminants may be encountered in indoor environments. These contaminants can be generated by a number of sources. Among the potential contributors to indoor air pollution are combustion sources such as appliances. Other indoor air pollution sources include radon gas, usually from the soil underlying a home, and organic chemical vapor emissions from various substances (e.g., building materials and consumer products) typically found within a home. Technically, indoor air quality problems involving radon gas and building materials can be considered separately from combustion sources since radon and organic compounds from building materials are not generated by combustion.

This handbook addresses indoor air quality in the residential environment as it is affected by combustion sources. Information is provided for both non-technical and technical persons on the current state of knowledge regarding combustion sources and indoor air pollution. The following information is summarized: health effects of combustion-generated pollutants; pollutant emission rates of combustion sources; factors affecting pollutant concentrations; results of residential monitoring surveys; available monitoring equipment and control techniques; air quality standards and guidelines; and modeling techniques.

This handbook is an update of a previous handbook documenting the state of knowledge regarding combustion sources in the indoor air environment (1). This revised edition draws from over 400 of the latest and most important references in the scientific literature in presenting a compilation and review of indoor air quality as influenced by combustion sources.

For the purposes of this handbook, a combustion source is considered to be any process that involves the burning of wood, natural gas, petroleum-based fuels, or other carbon-based substances within a residence. Important indoor combustion sources that may be present in a home include unvented gas space heaters, woodburning appliances (e.g., stoves, fireplaces, and heaters), unvented kerosene-fired space heaters, gas-fired appliances (e.g., ranges and ovens), and tobacco products (e.g., cigarettes, pipes, and cigars). Although other combustion sources may exist and can be significant in individual homes, their effects are not as well documented in the literature. Automobiles in attached garages and miscellaneous gas-fired appliances such as clothes dryers would be considered in this latter category.

All combustion sources emit to varying degrees and in varying proportions many of the same pollutants: carbon monoxide, nitrogen dioxide, and particles suspended in the airstream (smoke), as well as a wide variety of other pollutants in smaller quantities. Although carbon dioxide and water vapor are also common products of combustion and are emitted in substantial quantities by most combustion sources, the emission of these combustion products is not often cited as a major hazard in indoor air.

The health and welfare of the public is the primary concern of the government regarding indoor air quality. Not only does poor indoor air quality degrade the quality of life, but there are also lost work hours, lowered productivity, and increased health care costs, which represent an economic burden individually and collectively. In the past, federal and state agencies have been responsible for ensuring that human activities in the workplace or outdoors do not create unreasonable hazards to human health. In recent years, it has become apparent that indoor air may at times present hazards greater than those encountered either in occupational or outdoor settings. The health implications are made more serious by the fact that most people spend 80-90 percent of their time indoors.

HEALTH EFFECTS OF COMBUSTION-GENERATED INDOOR AIR POLLUTANTS

Because Americans spend an average of more than 16 hours a day at home, and much of the time away from home is spent indoors (at work, shopping, school, etc.), indoor concentrations of pollutants from combustion have a large influence on total exposure. Until recently, little information was available on indoor concentrations of these pollutants. With respect to health, indoor pollutant concentration data are important because:

- Most pollution measurements are made outdoors, and the correlations between outdoor and indoor concentrations are poor; as a result, little is known about total exposures, which include indoor and outdoor exposures.
- Epidemiological analyses are often based on outdoor pollutant concentrations; consequently, they provide little information on the relationships between total exposures and health effects.

Combustion products of general health significance indoors include nitrogen oxides, carbon monoxide, and particles. Other combustion products can be important in special situations.

Nitrogen oxides are irritants that affect the functioning of the lung, including the lung's defense mechanisms against inhaled particles and gases. Effects observed to date at concentrations occurring indoors include:

- Increased reactivity of airways to other irritants (including other pollutants), especially in individuals with pre-existing hyper-reactive airways from asthma or acute respiratory infection
- Increased incidence of acute respiratory infection, especially in infants and children
- Potential impairment of long-term development of the lung from childhood respiratory infections.

Carbon monoxide binds with hemoglobin, thereby reducing the oxygen-carrying capacity of the blood. The effects are the same as, and combine with, other factors that reduce the oxygen available to body tissues, including chronic lung disease, circulatory disorders, and high altitude. Effects at concentrations occurring indoors (especially from smoking) include:

- Loss of alertness, impaired vision, and loss of dexterity
- Decrements in heart function in the physically impaired, increased incidence of myocardosis, and increased probability of heart failure among susceptible individuals.

Particles affect health out of proportion to their concentration in the atmosphere, because they deliver high concentrations of many potentially harmful substances directly to lung tissues. The result can be physical irritation, chemical irritation, chemical-specific toxicity, or carcinogenicity. Particle size is important because it affects where in the lung the particles are deposited and therefore, which tissues are exposed. Frequently in the discussion, the distinction is made between particles which, by virtue of their small size are inhalable into the small airways of the lung (referred to as respirable suspended particles or RSPs) and the total amount of suspended (respirable and non-respirable) particles (TSPs). Effects of airborne particles at concentrations occurring indoors include:

- Impairment of respiratory mechanisms
- Aggravation of existing respiratory and cardiovascular disease
- Morphological alterations
- Carcinogenesis
- Mortality from respiratory infections, cancer, or heart failure.

EMISSIONS FROM COMBUSTION SOURCES

A number of individual combustion sources may be present and operating in a given home, and each combustion source may release a significant amount of pollutants into the indoor air. The two most common measures used to evaluate the emissions characteristics of different classes and types of combustion sources are pollutant source strength and pollutant emission rate. A considerable portion of indoor air quality research is devoted to the measurement of these two characteristics of combustion sources.

The amount (weight or volume) of pollutants emitted into the indoor air environment over a given time period by a specific combustion source is referred to as its source strength. To a large degree, the source strength of a given combustion source is determined by the amount of fuel consumed over the given

time period (the "firing rate"), the degree to which the products of combustion are diverted to the outdoors (the "degree of venting"), and the amount of pollutants generated per unit of fuel consumed (the "emission rate").

Because of their potential impact on indoor air quality, unvented combustion sources are an important focus of indoor air quality research. Tobacco smoking, kerosene space heaters, and gas space heaters are usually unvented. Gas ovens, gas range burners, wood-fired appliances, and fireplaces may also become unvented due to improper operation or malfunctioning venting systems. When an unvented combustion source is operated, the firing rate and emission rate determine the composition and quantity of pollutants emitted into the indoor environment. The emission rate of a given combustion source is highly sensitive to factors related to its design and operation. As a consequence, much indoor air quality research is devoted to the question of what designs and operating procedures are most effective in minimizing the measured emission rates of the more hazardous pollutants.

Figure 1-1 shows the ranges of carbon monoxide, nitrogen dioxide, and particle source strengths which have been reported in the literature for several unvented combustion sources. Reported pollutant source strengths vary widely, not only across different types of combustion sources but within specific source types as well. Assuming proper maintenance and operation, different types of combustion sources tend to emit products of combustion in certain characteristic proportions and amounts due to varying fuel firing rates and burner designs. For example, the highest carbon monoxide source strengths have been reported for gas space heaters, while convective kerosene heaters tend to emit more nitrogen dioxide, but less carbon monoxide than radiant kerosene heaters.

The variability of measured emissions from combustion sources other than tobacco smoking is the result of factors which may be either specific to a given appliance, applicable to a certain type of appliance, or applicable across all types of combustion sources. Factors related to the operation of a specific appliance are often the most important in determining its source strength, since even the most well-designed appliance can be made to emit large amounts of pollutants if it is allowed to operate improperly. However, some types of combustion sources tend to emit pollutants in different amounts and proportions than other types, and certain general considerations apply to pollutant emissions from all types of combustion sources. Important appliance-specific factors which can increase emission rates include burner tuning, appliance maintenance, and firing rate. All of these factors increase emissions by reducing the efficiency with which the fuel is burned.

Studies have found that measured emission rates vary by age, brand, and model in all types of combustion appliances. Older models tend to have higher emission rates than newer appliances, a factor which may be due to improved designs or degradation of appliance performance over time. Variations in emission rates by brand name and model may be a consequence of variations in design and quality of construction between appliance manufacturers. It has been determined that when combustion occurs at low efficiencies at constant fuel consumption, unnecessarily high proportions of one or more pollutants may be produced. Low fuel combustion efficiencies can be caused by such factors as

Figure 1-1. Range of Reported Source Strengths for some Combustion Sources

Source: EA Mueller, Baltimore, Maryland

improperly adjusted flames, poor burner design, or operation of an appliance outside of its recommended firing range (i.e., over-firing or under-firing). Combustion efficiency is determined in part by the temperature at which combustion takes place. Low temperature combustion produces greater amounts of carbon monoxide and particles, while high temperature combustion produces greater amounts of nitrogen oxides. In turn, combustion temperature is strongly influenced by the relative proportions of air and fuel to the burner. Optimum appliance tuning depends on the proper balance of fuel and combustion air to minimize pollutant emissions.

FACTORS AFFECTING INDOOR AIR QUALITY

The level of combustion-generated air pollutants in a given home is determined by several factors:

- Source strength of the combustion sources present
- Air exchange rate
- House volume and rate of mixing
- Concentration of pollutants in the outdoor air
- Degree of reactivity (if any) of each pollutant.

For a given home, these factors are in turn determined by a large number of sub-factors (see Figure 1-2). Since many of these sub-factors are interdependent and may also vary widely with time, accurate prediction of indoor levels for a given home is often not possible. However, insight into the relative importance of these factors in determining combustion-generated pollutant levels in a home can be extremely useful in averting or correcting indoor air quality problems.

The air exchange rate of a home refers to the rate at which the volume of air within the home is replaced by outdoor air. It is often measured in air changes per hour and is a product of the air infiltration rate, forced ventilation (if any), natural ventilation (the opening of doors and windows), and all other mechanisms by which a house "leaks." Air exchange has the effect of diluting and "flushing out" pollutants which accumulate indoors and improves the quality of indoor air to the extent that the outdoor air is pollutant-free. Forced ventilation refers to the use of fans connected to outdoor air intakes for providing positive ventilation. In commercial buildings, code-mandated ventilation rate standards for occupied spaces are usually achieved through forced ventilation systems. However, most homes are not provided with forced ventilation. Residential heating, ventilation, and air conditioning systems typically are designed with the implicit assumption that adequate fresh air will be provided by natural ventilation (open windows and doors) and air infiltration through leaks in the building shell. When the infiltration rate of a home is reduced by weatherization (which lowers infiltration by sealing air leakage pathways), indoor air quality problems can be caused or exacerbated, due to the resulting decrease in fresh air intake, especially when strong pollutant sources are present.

Figure 1-2. Factors Affecting Indoor Air Quality

Source: Traynor, G.W., et al., Macromodel for Assessing Residential Concentrations of Combustion-Generated Pollutants: Model Development and Preliminary Predictions for CO, NO₂, and Respirable Suspended Particles, Report No. LBL-25211, Lawrence Berkeley Laboratory, Berkeley, California, January 1989.

Large pollutant source strengths are often cited as major contributing factors to residential indoor air quality problems. As mentioned previously, the pollutant source strength for a given home is a function of the effective emission rates of each pollutant from each combustion appliance within the house and the amount of time they are used. Each combustion appliance typically produces combustion-generated pollutants at rates and in proportions which vary according to its class, design, usage, whether it is vented or unvented, and the way it is installed and maintained. High pollutant source strengths result from continuous use of combustion sources with relatively high emission rates.

When combustion-generated pollutants are allowed to be dispersed throughout the home as a result of diffusion and convection, they will tend to become mixed with the air throughout the house volume. The resulting concentration in a theoretically completely mixed house is inversely proportional to the house volume. Thus, homes with larger volumes have more air to dilute pollutants than smaller homes and will generally have lower concentrations, given comparable air exchange rates and pollutant source strengths.

Since outdoor air is constantly introduced into most homes through infiltration and natural ventilation, the level of pollutants in outdoor air strongly influences indoor air quality. In most cases, outdoor air pollutant levels are much lower than those found indoors, and increased air exchange has a beneficial influence on indoor air quality since more pollutants are removed than introduced. However, in certain areas, outdoor pollutant levels can be significant and, thus, have a negative impact on indoor air quality. In cases where the level of one or more outdoor air pollutants is high, elevated baseline levels of these pollutants in the indoor environment usually result.

Some combustion-generated pollutants may be removed from the indoor air by reaction on surfaces. For instance, nitrogen dioxide is removed from indoor air by reaction on many indoor surfaces (including particle surfaces); as a result, indoor air can be lower in nitrogen dioxide than outdoor air. Particulates can be effectively removed from the air through the use of air cleaning devices. Chemically stable combustion products, such as carbon monoxide and carbon dioxide, are generally not thought to be significantly removed from indoor air by reaction.

Pollutant concentrations in a residence vary with location and time of measurement. Peaks occur initially near the pollutant source until dispersion and removal mechanisms produce more uniform concentrations throughout the house. For intermittent emissions, these peaks can exist for a relatively short period of time. Once the emissions stop, the concentration drops off, due to air exchange and/or pollutant reactivity. Under these circumstances, the average pollutant concentration can be much lower than the peak concentration. Pollutants that are emitted at a relatively constant rate will result in more constant indoor pollutant concentrations, although variations in other factors may cause fluctuations. With relatively constant emission rates and other factors remaining relatively constant, the average concentration over time may not differ significantly from the peak concentration.

In general, empirical data suggest that with intermittent sources, the source emission rate, house volume, and rate of mixing are the primary factors affecting peak pollutant concentrations. However, over time, the source emission rate and duration, the outdoor pollutant concentration, and the air exchange rate are the primary factors affecting long-term average pollutant concentrations. The influence of the pollutant reactivity rate in general is uncertain, with wide ranges in reactivity rates reported in individual building studies. In addition, uncertainties exist as to whether it is periodic exposure to short-term peak concentrations or long-term exposure to low concentrations which is more damaging to health.

INDOOR AIR POLLUTION MONITORING

A capability to obtain an objective measure of the level of pollutants in indoor air is important, both as a research tool and as a public health measure. In indoor air quality research, pollutant monitoring aids in the development of effective control measures as well as in the identification of structural characteristics and occupant habits which may affect indoor air quality. Indoor air pollution monitoring surveys are often conducted for the purpose of screening large numbers of homes. Data obtained from monitoring surveys aid in scientific research, formulating effective public health policy, and the identification of specific homes with indoor air quality problems so that the affected homeowners can undertake appropriate control measures.

Equipment suitable for monitoring combustion-generated air pollutants in homes has been developed for a number of applications, and is available in a wide range of costs and capabilities. For example, real-time laboratory instruments are available which can measure combustion-generated pollutants to an adequate degree of accuracy, but these instruments are generally expensive to procure and operate. Inexpensive passive monitors, which yield a measure of the average concentration of pollutants over time, are widely available for use in workplace environments. Although passive monitors which can measure major combustion-generated pollutants are available, these monitors are generally designed to detect pollutant levels which are higher than those expected in most residential environments. The main exception to this rule is nitrogen dioxide, which can be measured accurately at low levels using passive monitors. A passive monitor suitable for measuring low levels of carbon monoxide is under development.

Residential indoor air quality monitoring studies generally involve either small-scale, but intensive monitoring of test homes or monitoring of large numbers of homes using passive samplers. Small-scale monitoring studies using sophisticated measurement techniques are often performed to develop or confirm indoor air quality models or to investigate the effects of specific factors on indoor air quality. Large-scale monitoring surveys yield statistical data on the frequency and magnitude of indoor air quality problems across housing stocks which can be useful for a number of purposes. Results from these types of studies are typically used to develop estimates of the number of people at risk for adverse health effects, to correlate indoor concentrations to specific combustion sources, or to identify the sources or source usage practices which may lead to indoor air quality problems.

INDOOR AIR POLLUTION CONTROLS

The control of combustion-generated indoor air pollutants may be accomplished through several techniques:

- Source removal
- Increasing the air exchange rate of a home
- Direct removal of pollutants from indoor air
- Minimization of source emissions.

Within each of these techniques, various methods are available which vary in their degree of effectiveness and cost. An effective control technique may depend on a specific device to be purchased, a modification of given practices within the home, a repair to a defective or poorly maintained appliance, or other options. Usually, the least expensive options are repairing a defective or poorly maintained appliance and modifying appliance usage patterns.

The selection of the control methods or strategy most suitable to correcting or preventing a specific indoor air pollution problem can be exceedingly complicated. The proper choices for indoor air pollution control often depend heavily on the singular aspects of the particular home in question: the sensitivity of its occupants, the characteristics of the structure, pollutant sources and locations within the home, and the quality of the ambient air. Additional factors which may play a role in selecting appropriate controls are issues related to making the best use of space, the costs and required effectiveness of the controls, the pollutants involved, and many practical considerations of installation, operation, and maintenance. Table 1-1 lists various combustion-generated pollutant control strategies and methods, their effect on pollutant levels, and the types of cost associated with each measure.

Increasing the air exchange rate of a home will simultaneously reduce the level of all indoor air pollutants if the outdoor air concentrations are lower. However, increasing the air exchange rate of a given home also normally results in increased heating and cooling costs. Heat recovery through the use of air-to-air heat exchangers can be employed to reduce these costs. In general, increased air exchange rate is particularly desirable as a control method when a number of pollution sources of equal magnitude are present in a home.

Air cleaning devices remove pollutants from the indoor air. At the present time, however, residential air cleaning is practiced virtually exclusively for the control of particulates and odors, mostly through the use of filters or electrostatic precipitators (electronic air cleaners). Many high-efficiency carbon-based filters also enhance the removal of nitrogen dioxide and odors. While air cleaners used in industry are technically suitable for the control of some other combustion-generated contaminants, these types of equipment are not generally feasible for home use because of their high costs.

Source emissions can be reduced by altering source usage patterns, replacing certain appliance types with cleaner types, or improving the emission characteristics of a given appliance. Source usage patterns which may lead to

TABLE 1-1. CHARACTERISTICS OF RESIDENTIAL POLLUTION CONTROL METHODS

CONTROL STRATEGY	CONTROL METHOD	EFFECT ON POLLUTANT LEVELS	ASSOCIATED COSTS
Source Removal	Material or Product Substitution	Eliminates pollutants emitted from the source	Costs for installation and operation of substitute
	Restrictions on Source Use, Sales or Activities	Eliminates pollutants in restricted areas from the source	Costs for enforcement
Source Modification	Design or Usage Modifications	Reduces pollutant emissions from the source	Costs for installation and operation of incorporating new design
Air Exchange	Infiltration	Reduces pollutant concentrations provided outdoor concentrations are lower than indoor	Costs for heating and/or cooling increases with increasing infiltration
	Natural Ventilation	Reduces pollutant concentrations provided outdoor concentrations are lower than indoor	Costs for heating and/or cooling increases with increasing ventilation
	Mechanical Ventilation	Reduces pollutant concentrations provided outdoor concentrations are lower than indoor	Costs for installation and operation
	Local Ventilation	Removes pollutants from nearby source before they spread to rest of house	Costs for installation and operation
	Filtration	Removes airborne particles; generally not effective in removing gaseous pollutants	Costs for installation and operation
Air Cleaning	Electrostatic Precipitation	Removes airborne particles; generally not effective in removing gaseous pollutants	Costs for installation and operation
	Ionization	Removes airborne particles; generally not effective in removing gaseous pollutants	Costs for installation and operation
	Absorption	Removes gaseous or vapor pollutants; however, generally not suitable for residential use	
	Adsorption	Removes gaseous pollutants; generally not effective for gases with low molecular weights	

* Not generally available for residential use

Sources: Sandia National Laboratories, Indoor Air Quality Guide for Designers, Builders, and Users of Energy Efficient Residences, Albuquerque, New Mexico, November 1981.

EA Mueller, Baltimore, Maryland

increased emissions from a particular appliance include the misuse of gas ovens for space heating, the improper adjustment of the flame on kerosene space heaters, or the use of unvented gas space heaters in inadequately ventilated spaces. Poorly maintained combustion appliances may be emitting abnormally large amounts of pollutants into the home. Reducing source emissions is often the simplest and most cost-effective method for controlling indoor air pollution, especially when only one or two important pollutant sources are present. In some cases, substitution of non-polluting sources such as electric-powered versus gas-fired space heaters may be advised. Finally, the effective indoor emission rates of many combustion sources can be reduced by following recommended maintenance service and/or improving the installation design to provide or improve exterior venting.

INDOOR AIR QUALITY STANDARDS

Currently, there are no mandatory standards with regard to the quality of air in the residential environment, and it is unlikely that mandatory standards for the residential environment will be enacted in the near future, due to a number of unresolved issues. These include:

- Administration--the responsibility for and the means of administering any indoor air quality regulation in private homes are unclear at best.
- Health risk--the health risks associated with prolonged exposure of humans to low pollutant concentrations are controversial, promising to complicate the issue of setting allowable pollutant levels.

However, a number of guidelines have been developed to evaluate indoor air quality in the residential environment. Guidelines that are currently used to quantify or preclude indoor air quality problems are derived from ambient (outdoor) air quality standards, occupational standards, and building design standards.

Ambient air quality standards are often used for evaluating indoor air quality. However, a number of issues have been raised as to the validity of this approach. These issues include:

- The exposures of most people to indoor air pollutant levels are much greater than their exposure to outdoor air pollutant levels, since most of the U.S. population spends a majority (80-90 percent) of its time indoors.
- The most vulnerable segments of the population as far as health is concerned (i.e., infants and aged) are those most likely to spend the greatest portion of their time indoors.

Occupational health standards, which were developed to protect workers in industry, are also used as a basis for the development of residential pollutant level guidelines. Guidelines developed from these standards stipulate reasonable residential pollutant levels at 1/10 of occupational standards.

Building design standards, developed by private organizations and adopted into many building codes, are meant to preclude the development of indoor air quality problems in new buildings through the specification of minimum ventilation rates. These standards are most easily applied to commercial or high-rise building ventilation systems, however. Pollutant level standards are formulated for each pollutant on the basis of maximum allowable average and peak concentrations. These standards are designed to set limits on the continuous or instantaneous exposure, respectively, of people to pollutants that are known to have adverse health effects.

MODELING INDOOR AIR QUALITY

Mathematical modeling is an important tool in the field of indoor air quality, both as a means for studying the factors that influence concentrations of indoor air pollutants and as a basis for estimating indoor air pollutant concentrations in homes. A proper understanding of the relative importance of factors such as source strength and air exchange rates as they influence indoor air quality is essential to the development of effective measurement and mitigation techniques. Since direct monitoring of all homes in the United States is economically impractical, modeling techniques present an economically feasible means for assessing population exposure.

Although the fundamental principles of most mathematical models are well-established, a large number of factors that determine indoor air quality are also unique to every home. This fact tends to compromise the predictive ability of mathematical models with regard to individual homes. However, models have been developed which can predict the statistical variations across large numbers and classes of homes.

PERSPECTIVE FOR HOMEOWNERS

Currently, there are no inexpensive or readily available methods for homeowners to precisely measure or accurately estimate the levels of most combustion-generated pollutants in their homes. Homeowners may, however, minimize the amount of combustion-generated pollutants in their homes by implementing a variety of control measures. Since these control measures vary in cost and difficulty, a level of understanding of the factors which influence indoor air quality may help the homeowner to pinpoint the most probable causes of pollutants. The simplest methods for maximizing indoor air quality involve following common sense procedures for the use of combustion sources and being more selective in the purchase of such appliances. Examples of these procedures include removal or modification of pollutant sources and increasing the effective air exchange rate of a residence. More active measures involve the cleaning of indoor air with a range of filtration devices.

Monitoring surveys, modeling efforts, and laboratory research all work to further our understanding of indoor air quality. Surveys of combustion-generated pollutant levels within large numbers of homes have shown that combustion-generated pollutants are sometimes present in homes at levels which are higher than outdoor air standards or indoor air quality guidelines. At the present time, the distribution of combustion-generated indoor air pollutant levels throughout the United States housing stock is not well known, but indoor air

research is being pursued which will provide improved estimates in the future. Such research programs (applied or theoretical) provide a basis for estimating health risks to the population as a whole and give further information about the characteristics common to homes with elevated indoor air pollutant levels. Research into how these and other factors influence the quality of air in the residential environment aid in the characterization of indoor air quality problems and in the formulation of appropriate and cost-efficient control strategies.

SCOPE AND ORGANIZATION OF HANDBOOK

This handbook addresses the major factors associated with residential combustion sources and their impact on indoor air quality. Quantitative and descriptive data are presented in a summary format to help both the non-technical reader (i.e., the homeowner) and technical persons (with an interest in indoor air quality issues) to understand the current state of knowledge regarding combustion sources of indoor air pollution. These data have been compiled from government and privately funded research results, conference proceedings, technical journals, and recent publications. References are provided at the end of each section for those wishing more detailed information.

This handbook is divided into nine chapters. Section 1, Introduction and Summary, summarizes the indoor air quality issue and reviews the scope, purpose, and organization of the report. Section 2, Health Effects, reviews the state of knowledge regarding health effects from combustion pollutants, with emphasis on carbon monoxide, nitrogen dioxide, and particles. This information will help the reader to associate data on emission source strengths and rates and indoor pollutant concentrations with the pollutant levels believed to cause health effects. Section 3, Emissions from Combustion Sources, is organized by individual combustion source. For each source, data on the types of pollutants, their typical source strengths and rates, and factors influencing them are provided. The ultimate impact of pollutant emissions on indoor air quality is dependent on a number of Factors Affecting Pollutant Concentrations, as discussed in Section 4. These include source emission strength and rate, house volume and rate of mixing, air exchange rate, and reactivity. Typical Indoor Concentrations resulting from the operation of gas stoves, space heaters, woodstoves, and from smoking have been identified in monitoring and modeling studies. Section 5 summarizes the results of these studies and describes methods used to measure and monitor indoor combustion pollutants. Section 6, Control Techniques, discusses strategies for controlling indoor levels of pollutants, including source removal and modification, air exchange, and air cleaning. Section 7, Indoor Air Quality Standards, lists and discusses the ambient and occupational air quality standards and ventilation standards which have been used to control or provide guidelines for indoor air quality. A review of models which can be used to predict the impact of combustion devices on indoor air quality is included in Section 8, Models. Finally, Section 9, Perspective for Homeowners, presents information in layman's terminology on combustion-generated indoor air pollutants.

The appendices contain supporting information. Appendix A provides a listing of manufacturers supplying monitoring equipment and Appendix B presents the background data and analyses available to estimate nitrogen dioxide concentration in homes. Appendix C is a glossary of terms used throughout the report.

A few words are in order regarding the physical units used in the text, graphs, and tables. Due to the broadly international nature of the research reported herein, the physical units of measure have been left as they were originally reported. Thus, both SI and English engineering units are used, and no attempt has been made to convert to a uniform system nor to provide dual scales or converted values other than in isolated instances. Since, in the great majority of cases, the interest is in presenting comparative information on combustion-generated indoor air pollutants, it is felt that relative differences will be clearly reflected regardless of the system of units employed in specific cases.

REFERENCE

1. Mueller Associates, Inc.; Indoor Air Quality Environmental Information Handbook: Combustion Sources, Report No. DOE/EV/10450-1, for U.S. Department of Energy, Washington, D.C., January 1985.

Section 2

HEALTH EFFECTS

INTRODUCTION

On average, Americans spend more than 16 hours per day at home, and much of their time away from home is spent indoors at work, shopping, school, etc. (1,2). Indoor pollutants, therefore, have a large influence on total population exposure to pollutants from all sources. It has only been in the last two decades, however, that attention has focused on indoor pollution concentrations outside places of work (3).

Indoor pollution exposure is important to health, with the actual impact determined by the relationships between pollution dose (concentration times time of exposure) and health response to that dose. Much of the knowledge of pollution dose-response relationships under real-world conditions is derived from epidemiological studies based on statistical analysis of outdoor pollution concentrations and indices of health effects. Few studies include measured concentrations indoors. The statistical relationships are valid only to the extent that measured outdoor concentrations are good indices of total exposure indoors and outdoors. If they are not, they can introduce error into the estimates of dose-response relationships. Thus,

- If pollutant concentrations are lower indoors than outdoors, and a statistical relationship is found between outdoor concentrations and some measure of health effect, then the relationship will appear to be smaller than it really is. This is because health effects are occurring at a lower average concentration than measured and/or the rate of increase of the dose-response relationship per unit increase in exposure is lower than it would be were the true exposure known.
- If pollutant concentrations are higher indoors than outdoors because of indoor emission sources, then the time and space patterns of indoor and outdoor concentrations can be different and probably uncorrelated. Under this condition, statistical analysis could fail to find a true relationship between pollution exposure and health effect because the measured index of exposure (i.e., outdoor concentration) has a different distribution from the dominant indoor exposures and the resulting health effects.

The net result of the above errors is to cause underestimation of the true dose-response relationship, if any, either because the true effects occur at concentrations lower than is thought or because there are true effects that cannot be discovered using outdoor concentrations as measures of total exposure.

The uncertainty introduced to epidemiological studies by indoor air pollution acts with several other sources of uncertainty. For example,

- Measures of outdoor concentrations are usually taken from a limited number of monitoring stations. These stations are often established to determine compliance with environmental regulations; as a result, they tend to be placed where concentrations are expected to be high. They are usually not representative of the geographic average level of exposure in the area, and they are certainly not representative of exposure to a person moving about in the area.
- There is evidence for some pollutants (nitrogen dioxide, for example) that most of the observed health effects are produced by peak exposures, not average exposures (4). Peak concentrations are not necessarily correlated with average concentrations.
- Frequent migration of Americans means that current exposure, however estimated, is not necessarily representative of long-term average exposure.
- Important variables affecting health, such as smoking, age, nutrition, and income, are often not included or are incorrectly or inadequately included in epidemiological studies.
- Incidences of potential air pollution health effects are often inadequately or incorrectly reported.

The effect of these uncertainties is to reduce severely the ability to find dose-response relationships for air pollution health effects at the low levels to which people are normally exposed, and to reduce the confidence that might prevail in the few relationships that are available. Even when the mechanisms of health effects are well understood qualitatively, it is always difficult and often impossible to make quantitative estimates or to predict specific effects and numbers of individuals affected.

There is a large and well-reviewed literature on the health effects of air pollution. Most of the information presented in the following sections has been taken from the reviews listed in the Bibliography, especially the Criteria Documents from the U.S. Environmental Protection Agency (EPA). Specific references are provided only where necessary for clarity.

NITROGEN OXIDES

The term nitrogen oxides (NO_x) refers to a number of compounds--nitric oxide (NO), nitrogen dioxide (NO_2), nitrous oxide (N_2O), nitrogen trioxide (NO_3), dinitrogen oxide (N_2O_3), nitrogen tetroxide (N_2O_4), and nitrogen pentoxide (N_2O_5)--all of which have the potential to affect human health. In addition, secondary reaction products, such as nitrate aerosols, may be harmful. By far, most is known about the effects of NO_2 , which has been studied extensively over the past 30 years. In addition, NO persists longer indoors than outdoors; as a result, its effects should be included when evaluating the indoor environment.

Overview

There is evidence that NO_x (or their derivatives), particularly NO_2 , may be harmful to human health at levels of exposure that can occur indoors. Recent studies show that:

- There may be an immediate short-term effect in the form of an increase in airway reactivity (sensitivity). This heightened reactivity can make airways more vulnerable to non-specific, irritant stimuli (such as other pollutants) and cold or dry air. The effect appears to follow episodes of short-term, high concentrations. Individuals with pre-existing hyper-reactive airways from asthma or acute respiratory infections (current or recent) are likely to be most susceptible.
- There may be an increasing incidence of acute respiratory infections from exposure to NO_2 , especially in infants and children. This effect is more likely to follow repeated exposures. There is also evidence that acute respiratory infections in childhood increase the probability of developing chronic lung disease in adolescence and adulthood, retarding growth and development of the lung, or both. The direction of causality is not clear.
- Exposure to NO_2 may impair lung function in children. This effect is also more likely to follow repeated exposures. If the changes persist into adulthood, they can cause reduced lung growth or accelerated aging of the lung.

Mechanisms of Toxicity

There is some disagreement about the specific mechanisms of NO_2 toxicity. Animal studies suggest that it may react with water in the lung to form nitrous and nitric acid, or it may react with readily oxidizable proteins and lipids in tissues, including lecithin which is a major constituent of cell membranes, to form nitrite ion. In either case, the resulting ions can:

- Produce general chemical irritation of all exposed tissues and increase sensitivity to other irritants.
- Impair chemical and functional properties of membranes. One result is dysfunction of defense mechanisms against respiratory infection, including reduced rates of mucociliary clearance and reduced activity of alveolar macrophages. Another result is reduced rates of gas exchange.
- Suppress or activate immune responses of antibodies and lymphocytes.

- Alter structural proteins such as elastin and collagen, which impairs the mechanical and structural integrity of lung tissues. Emphysema-like changes have been observed at very high exposures.
- React with hemoglobin to produce methemoglobin which, like carboxyhemoglobin from carbon monoxide exposure, reduces the oxygen-carrying capacity of the blood.

Formation of highly ionized acid in the respiratory tract probably causes the observed acute irritant effects of NO_2 exposure. Potentially carcinogenic nitrosamines can be formed in the respiratory tract or even more rapidly in the acid environment of the stomach. These may also contribute to liver dysfunction.

Antioxidant defense mechanisms are important mediators of responses to NO_2 . Vitamin C supplements decrease the effects.

Tissues most susceptible to the effects of NO_2 exposure are those of the lower respiratory tract--the terminal bronchioles and adjacent alveolar ducts and alveoli. Within these regions, the cells of the ciliated epithelium receive high doses.

Most of the information associated with these mechanisms has been obtained from animals exposed to NO_2 concentrations that are much higher than those occurring in natural environments, except possibly in industrial accidents. Non-carcinogenic effects in humans are similar to those in other animals, but they occur at different levels of exposure. Carcinogenic effects in humans, including those of nitrosamines, generally do not correspond well to those in other animals.

Clinical Research

Controlled exposures of human volunteers to NO_2 emissions have been confined to periods of several hours or less, administered once or on several successive days; as a result, they provide little information on the chronic effects of long-term, low-level exposure. Functional and chemical recovery from these brief, high-concentration exposures tend to be rapid, and it is not known whether repeated exposures at these levels can act cumulatively or predispose the lung to permanent damage. The short-term, reversible effects can, however, aggravate pre-existing functional disorders (mostly cardiopulmonary) or reduce the resistance of the respiratory system to infection.

Studies of the effects of low concentrations of NO_2 on breathing rates and volumes, respiratory mechanisms, distribution of gas in lungs, gas exchange rates, and diffusion capacity of lungs have shown that impairment is generally not observed in healthy subjects or patients with bronchitis at or below 1.0 part per million (ppm) NO_2 . In some asthmatics, symptoms of irritation can occur from exposures as low as 0.3 ppm NO_2 .

Studies of the effects of low concentrations of NO_2 on airway reactivity, particularly among asthmatics, have shown the following:

- Hyper-reactivity of airways to non-specific environmental stress from cold air or other air pollutants and irritants has been reported at exposures in the range 0.2-0.5 ppm NO₂.
- In healthy adults, increased airway reactivity has been reported at exposures as low as 0.05 ppm NO₂, but more recent studies suggest that the lower limit is closer to 2.0 ppm NO₂.
- The odor threshold of NO₂ is about 0.04 ppm.

Although small changes in lung function and airway reactivity have been observed in asthmatics at low concentrations, no effects have been found at higher concentrations up to 4 ppm. There is currently no plausible explanation for this apparent lack of dose-response relationship. Some of this variability may be caused by differences in test conditions. More study is required.

Studies of the effects of low concentrations of NO and NO₂ on blood hemoglobin have shown that:

- NO and NO₂ are equally effective in producing methemoglobin.
- NO and NO₂ are about four times as effective as CO in reducing the oxygen carrying capacity of blood.

Epidemiological Research

Children have provided the most useful epidemiological information on the health effects of long-term NO₂ exposure. The most useful information comes from studies comparing children from homes with and without unvented gas cooking stoves. Children under two years of age appear to be most sensitive. Studies have shown the following effects:

- Differences in incidence of acute respiratory illness, presumed to be infectious, are reported in houses with and without unvented gas stoves. This corresponds with animal studies showing reduced ciliary action and injury of macrophages, both of which reduce resistance to infection by decreasing the rates of bacteria removal from the lungs.
- Differences in lung function are reported between houses with and without unvented gas stoves.
- Associations between outdoor NO₂ concentrations, altered lung function, and increased respiratory illness were reported in early studies of Chattanooga school children. These results are now questioned because of inadequate NO₂ measurement methods. More recently,

outdoor NO₂ concentrations have been shown to be associated with increased incidence of reported respiratory symptoms in 0-5-year old children in Switzerland.

- There is no consistent evidence that short-term exposure to NO₂ has an effect on respiratory illness.

Results tend to be consistent for younger children, but not for older children and adults. Some of the results are from questionnaires, which are subject to bias.

Although there appear to be qualitative relationships between existing long-term NO₂ exposures and health effects, the available data cannot support quantitative estimates of dose-response relationships.

Sensitive Populations

As is common for irritants, individuals at special risk from NO₂ exposure are those with existing lung disfunction and children, especially those under two years of age. In addition, from animal studies showing increased systemic, blood, and hormonal alterations after NO₂ exposure, there is reason to suspect that individuals with cirrhosis of the liver or other liver, hormonal, and blood disorders, or those undergoing certain types of drug therapies, may also be at special risk. Individuals with heart disease might be affected by the reduced oxygen-carrying capacity of blood from methemoglobin formation; this effect is additive with that of carbon monoxide (see below).

Interactions with Other Pollutants

The most important interaction of NO_x with other pollutants is their participation in photochemical smog formation reactions, which generate a broad range of harmful chemicals, including ozone and peroxyacetylnitrates (PAN). These reactions are not known to be important indoors. Other potentially important interactions include:

- Increased exposure times to inhaled particles because of reduced removal rates by ciliary and macrophagal action. This can increase risk of respiratory illness from inhaled bacteria and cancer from inhaled carcinogens.
- Reactions with gaseous amines to form potentially carcinogenic nitrosamines.
- Reactions with benzo(a)pyrene to produce the mutagens hydroxybenzo(a)pyrene, and 1,3- and 6-nitrobenzo(a)pyrene.
- Reaction with pyrene to form the mutagen 3-nitropyrene.

- Hemoglobin-binding by NO and NO₂, which is additive with that of carbon monoxide, but four times as effective per unit dose.

There is no evidence of synergistic effects with other irritant gases.

CARBON MONOXIDE

- Carbon monoxide (CO) is a poisonous gas which causes tissue hypoxia (oxygen starvation) by binding with blood hemoglobin and blocking its ability to transport oxygen and changing other oxygen-related characteristics. The binding affinity between CO and hemoglobin is 200 times that of oxygen. The product, carboxyhemoglobin (COHb), is an indicator of the reduction in oxygen-carrying capacity. CO apparently has no other deleterious effects at normal concentrations except some minor chemical and physical changes, the health significance of which is not clear. These include formation of carboxymyoglobin, which may disturb muscle metabolism, especially in the heart, other binding reactions of uncertain significance, possibly short-term increases in capillary permeability for proteins, effects on pacemaking signals in the heart, and effects on blood clotting mechanisms.

Overview

The effects of CO exposure and the resulting carboxyhemoglobin formation are essentially identical to those of other factors that reduce oxygen availability to body tissues, such as chronic lung disease, disorders reducing blood circulation, and high altitude.

- In the short term, carboxyhemoglobin reduces the oxygen-carrying capacity of the blood, which can cause tissue hypoxia. Asphyxiation occurs at exposures greater than about 1800 ppm for one hour.
- Under chronic exposure, such as from cigarette smoking, the body compensates somewhat by increasing the concentration of red blood cells and the total amount of hemoglobin available for oxygen transport. Smokers routinely have carboxyhemoglobin concentrations of 3-8 percent, well into the range known to cause health effects in non-smokers.
- The central nervous system and cardiovascular system are most sensitive to CO-induced hypoxia.
 - Health effects related to hypoxia of the central nervous system include loss of alertness and impaired perception, loss of normal dexterity, reduced learning ability, sleep disruption, drowsiness, confusion, and at very high concentrations, coma and death.

- Health effects related to hypoxia of the cardiovascular system include decrease in exercise time to produce angina pectoris (chest pain), increase in incidence of myocardosis (degeneration of heart muscle), and in general, increased probability of heart failure among susceptible individuals.
- Population groups at special risk of the detrimental effects of CO exposure include fetuses, persons with existing health impairments (especially heart disease), persons under the influence of drugs, and persons not adapted to high altitude who are exposed to CO and high altitude.

Mechanisms of Toxicity

CO is unusual among environmental pollutants in that its effect is directly observable as formation of carboxyhemoglobin in the blood. The chemical binding of CO to hemoglobin is much stronger than that of oxygen, and the combined form, carboxyhemoglobin, is more stable. In general, the CO-bound hemoglobin becomes unavailable for carrying oxygen, which reduces the total oxygen available to the body. A small amount of CO is produced naturally in the body by normal chemical breakdown processes, producing a normal concentration in unexposed persons of about 0.5 percent CO-bound hemoglobin.

Important factors influencing CO uptake and carboxyhemoglobin formation include:

- Time of exposure. About 16 hours are required for the blood to reach equilibrium after an increase in CO exposure. Removal of carboxyhemoglobin is at first rapid, then slower. Half-time is three to four hours.
- Breathing rate, which varies widely with exercise level from four liters/minute while sleeping to 20 liters/minute during heavy exercise.
- Endogenous CO production, the rate of which can be increased by as much as four times by some diseases and drugs.
- Gender, which affects blood volume, hemoglobin content (also affected by anemia, which is more common in women), lung volume, breathing rate, etc.

Central Nervous System Effects

Hypoxia (oxygen starvation) of the central nervous system causes a wide range of effects in the exposure range of 5-17 percent carboxyhemoglobin. These effects include loss of alertness and discrimination, loss of visual perception, reduced manual dexterity, and reduced learning ability.

- Loss of vigilance is reported at carboxyhemoglobin levels as low as 1.8 percent, but not all researchers have been able to replicate these results. Loss of vigilance is clear at 5 percent under some but not all experimental designs.
- Concentration-related decrements in dark adaptation are reported at carboxyhemoglobin levels of 5 percent.
- Hand-eye coordination is reduced in some complicated tests at carboxyhemoglobin levels of 5 percent.
- Marginal effects on central nervous system activity are reported at carboxyhemoglobin levels of 5-6 percent.
- Marginal effects on sleep are reported at carboxyhemoglobin levels of 8 percent.
- More severe impairment of central nervous system function occurs at carboxyhemoglobin levels in excess of 10 percent. These include headache, lassitude, general psychomotor problems, and at levels higher than 20-30 percent, nausea, vomiting, dimness of vision, convulsions, and coma.

Cardiovascular Effects

The lowest observed CO exposures producing human health effects are reported in individuals suffering from chronic angina pectoris, a symptom of cardiovascular stress in which mild exercise or excitement can cause pressure or pain in the chest from insufficient oxygenation of heart muscles. Reduced time of onset of angina pectoris from exercise are reported at carboxyhemoglobin levels as low as 2.0 percent, but some of these results have been questioned because of methodological inadequacies. The effect is clear at 2.9 percent. Other reported effects are:

- Suggestions of effects on cardiac function (p-wave abnormalities) at concentrations of 2.4-7.1 percent.
- Decreased work time to exhaustion in exercising healthy young men at carboxyhemoglobin levels of 3.3-4.3 percent.
- Decreased maximal oxygen uptake during strenuous exercise by healthy young men at 5-5.5 percent or more.

Increased risk of heart failure must necessarily occur in susceptible individuals at higher levels of exposure. For obvious reasons, it is not possible to test these individuals at the more risky levels; consequently, no data are available.

Sensitive Populations

Persons most sensitive to the harmful effects of CO exposure are:

- Fetuses and newborns, which develop at or near critical levels of oxygenation and, thus, can be affected even at moderate levels of exposure to CO.
- Elderly individuals, especially those with reduced heart and lung functions.
- Individuals with angina pectoris, poor blood circulation, and other cardiovascular diseases.
- Individuals with chronic respiratory diseases such as bronchitis, emphysema, and asthma.
- Individuals with anemia and/or abnormal hemoglobin type affecting ability to transport oxygen.
- Individuals taking certain drugs, including alcohol.
- Individuals not adapted to high altitude who are exposed to both high altitude and CO.

Individuals with combinations of the above conditions (e.g., elderly asthmatics with heart conditions) are likely to be most susceptible.

Interactions with Other Pollutants

There are no known synergistic interactions of CO with other pollutants except that NO₂ acts additively with it by also binding with hemoglobin and reducing the oxygen-carrying capacity of the blood. The total combined reduction in oxygen-carrying capacity can be estimated by multiplying NO plus NO₂ concentration (in ppm) by four to yield CO equivalents. Indirect interactions can occur through the ability of other pollutants to reduce lung function by increasing breathing resistance and decreasing lung surface area available for gas exchange. Since reductions in lung function are long term and effects of CO are short term, this linkage is remote.

PARTICLES

Particulate matter is a broad class of chemically and physically diverse substances present in the atmosphere as discrete particles, including liquid droplets. Particles present a risk to health that is out of proportion to their concentration in the atmosphere because they deliver a high-concentration package of potentially harmful substances directly to the tissues of the respiratory tract. Consequently, while few cells may be affected at any one time, those few that are can be badly damaged. Particle size, which affects the location and magnitude of deposition in the respiratory tract, and chemical composition, which determines the health effects of the deposited particles, vary over broad ranges, depending on source characteristics. Particles produced by indoor combustion can vary minute by minute, depending on combustion conditions. Because of this variability, it is exceedingly difficult to quantify the health effects of the

particle mixtures. Therefore, it is necessary to consider the effects of individual components of the mixtures from specific and well understood sources.

Overview

The health effects of airborne particles are directly attributable to: physical irritation by insoluble particles; chemical irritation by free radicals and acidic components of particle mixtures; and chemical-specific toxicity or carcinogenicity of the components of particle mixtures. Some health impacts are indirectly attributable to these effects through exacerbation of other pre-existing conditions. Major effects of concern are: impairment of respiratory mechanisms; aggravation of existing respiratory and cardiovascular disease; morphological alterations; carcinogenesis; and mortality from respiratory infections, cancer, or heart failure.

Populations at special risk from exposure to airborne particles include the following:

- Children and the elderly
- Individuals predisposed by some disease, such as asthma, bronchitis, cystic fibrosis, emphysema, or cardiovascular disease; some otherwise normal persons are hyperreactive to certain substances.
- Smokers
- Individuals who routinely breathe through the mouth.

The health effects of particles from active and passive cigarette smoking are well known but the health effects/dose-response information for other particles is badly confounded by effects of sulfur dioxide concentrations, which are normally high in the same areas as particle concentrations. Since many of the health effects of inhaling sulfur dioxide are similar to or the same as those of inhaling particles, especially sulfate particles formed from atmospheric sulfur dioxide, it is difficult to separate their relative contributions. Dose-response data for exposure to airborne particles, not from cigarettes, are, therefore, especially uncertain (5).

Particle Deposition

Particle size distribution is important in determining dose to lung tissues because size determines where inhaled particles deposit, if at all. In general, particles suspended in the atmosphere range in size from about 0.005-100 microns. They tend to occur in two size groups, separated at about 2.5 microns. Coarse particles (greater than 2-3 microns) are primarily mineral dust, sea salt, and plant material. Fine particles are further divided into those formed by condensation of combustion vapors (mostly soot and condensed organic compounds) and those formed by aggregation of smaller particles (mostly acid aerosols and their neutral salts)--0.005-0.05 microns and 0.02-3 microns or more, respectively. The two size ranges behave independently. Their distribution in any one place is a variable function of the complex combination of chemical and physical conditions under which they were formed.

Coarse particles tend to deposit high in the respiratory tract. At the upper levels, they are cleared by nose-blowing and sneezing; while at the lower levels, they are cleared by ciliary action to the esophagus, where they are swallowed. During nasal breathing, nearly all particles larger than 4 microns are deposited above the larynx. During oral breathing, penetration is much deeper. Complete deposition is only achieved for particles larger than 10 microns and 20-30 percent of particles of 5-10 microns are deposited in the trachea and bronchial airways. Harmful effects of particles deposited high in the respiratory tract, if any, occur through ingestion. Few coarse particles are produced directly by indoor combustion sources, although some may form indirectly through the uptake of gases or fine particles by water droplets.

Of the fine particles, about half of those that are hygroscopic (water seeking), such as sulfates and nitrates, deposit high in the respiratory tract, and the remainder, including any remaining coarse particles, are carried into the tracheobronchial and deep alveolar regions of the lung. In general, 10-20 percent of the particles less than one micron in size are deposited. About 20 percent of particles of 1-4 microns are deposited during nasal breathing, and 20-70 percent are deposited during oral breathing. The largest difference between oral and nasal breathing occurs at about 3.5 microns.

Hygroscopic particles take up water and grow in the atmosphere; high humidity has a particularly large effect. The increased size profoundly affects deposition characteristics, toxicity, and removal efficiency.

Little is known about deposition rates of particles in children, who inhale more air per unit body weight than adults and who are thought to be more susceptible to the effects of all pollutants. The few data available for children with asthma or chronic bronchitis, and results from lung models, suggest that deposition in children is higher than in adults. Peak deposition efficiency is at about two years of age, followed by a decline with increasing age.

In the upper parts of the lung, particle clearance is by mucociliary action. In the deeper parts of the lung (the alveoli), clearance of highly soluble particles is by absorption in the alveolar epithelium, penetration of endothelial barriers, and transport by blood or lymph to other tissues. Clearance of less soluble particles is by phagocytosis by alveolar macrophages and migration to ciliated passages. About 40 percent of particles deposited in the alveoli are transported out. The remainder is absorbed or accumulated as focal deposits within parenchymal tissues. Residence times for soluble particles are in hours, while those for insoluble particles are normally in days to months and can be years. Disease can reduce mucociliary clearance rates significantly.

Mechanisms of Toxicity

Although the respiratory tract is able to remove foreign material, if particle exposures are high or if clearance mechanisms are impaired, accumulation of particles can reach harmful levels. Two classes of particles produced by combustion that are important with respect to health effects are: acid aerosols and their neutral salts (mostly sulfates) and condensed organic particles. Mechanisms of effect are varied; for example,

- Chemical or mechanical irritation of tissues or nerve endings at the site of deposition can produce immediate or cumulative changes in lung tissues and mucous secretion.
- Alterations of host defense mechanisms--mostly ciliary clearance and alveolar macrophages--can increase susceptibility to infection and accelerate development of chronic lung disease.
- Morphological changes from direct or indirect tissue damage can lead to reduced lung function and aggravation of pre-existing lung disease.
- Systemic toxicity can damage lung tissues directly or toxins can be transported to other sensitive tissues throughout the body. Some components are also carcinogenic.

The rank-order of irritant potential of sulfate particles and that of their permeability are the same, with sulfuric acid being the most damaging (see Table 2-1). Short-term health effects tend to be related to their irritant potential, while longer-term effects are related to changes in lung function caused by irritation, which makes the lung more susceptible to additional irritation as well as to infection and toxic or carcinogenic effects of other pollutants.

Effects on Respiratory Mechanisms

Responses of respiratory mechanisms to particle exposure can range from mild, transient changes of little direct health significance to incapacitating impairment of breathing. Most long-term and some short-term epidemiological studies have shown that persons living in areas with high particle concentrations have a higher prevalence of respiratory symptoms (chest tightness, cough, phlegm, etc.) and lower lung function capability than persons living in areas with lower concentrations. Irritants such as acid sulfates and nitrates are particularly important. Ammonia, which is produced in the mouth (bad breath) and by common household cleaners, urine, pet boxes, etc., rapidly neutralizes these acid pollutants, significantly reducing their potency.

Changes in lung mechanics have been reported in animals at exposures as low as 100 microgram/cubic meter sulfuric acid for one hour, but not all researchers have been able to find measurable effects at this level. No short-term studies in humans show effects at levels below 100 microgram/cubic meter in the most sensitive individuals (asthmatics).

Aggravation of Existing Respiratory and Cardiovascular Disease

Particle-induced bronchoconstriction, mucus secretion, and other effects can aggravate bronchitis, emphysema, pneumonia, asthma, and influenza, and increase risk of heart failure from inadequate oxygenation of the heart. Interactions between particles and sulfur dioxide appear to be important to these effects. The EPA believes there may be a threshold for these effects at a 24-hour average concentration of 250-350 microgram/cubic meter particles of diameter less than 10 microns. There is no universal agreement about the existence of such a threshold.

TABLE 2-1. RELATIVE IRRITANT POTENCY OF SULFATE SPECIES
IN GUINEA PIGS

COMPOUND	IRRITANT POTENCY ^a
Sulfuric acid	100
Zinc ammonium sulfate	33
Ferric sulfate	26
Zinc sulfate	19
Ammonium sulfate	10
Ammonium bisulfate	3
Cupric sulfate	2
Ferrous sulfate	0.7
Sodium sulfate ^b	0.07
Manganous sulfate	-0.9

- ^a Data are for particles of 0.3 micron median diameter. The increase in airway resistance caused by sulfuric acid (0.41 percent increase/microgram sulfate as sulfuric acid) was assigned a value of 100. Exposure time = 1 hr.

- ^b At 0.1 microgram

Sources: U.S. Environmental Protection Agency, Air Quality Criteria for Particulate Matter and Sulfur Oxides, Report No. EPA-600/8-82-029, Research Triangle Park, North Carolina, December 1982.

Amdur, M.D., et al., "Comparative Irritant Potency of Sulfate Salts," Environmental Research, Vol. 16, pp. 1-8, 1978.

Altered Lung Defense Mechanisms

Particles in the deep lung (including bacteria) are normally engulfed by alveolar macrophages and/or cleared by ciliary action, which moves them to the esophagus where they are swallowed. Reductions in these functions, therefore, increase the risk of bacterial infection and increase the time of exposure to deposited particles. These effects create a positive feedback in which initial responses increase susceptibility of the lung to the following exposures; as a result, the response becomes increasingly worse as exposure continues.

Morphological Damage

Long-term exposure of animals to acid particles can produce alveolar lesions similar to early stages of emphysema. These effects are observed at concentrations much higher than those to which humans are normally exposed to over long periods. Insoluble particles can accumulate in the lungs and produce pneumoconiosis at concentrations near to slightly above those normally encountered in natural environments.

Cancer

Particles inhaled from cigarette smoking are a major cause of lung cancer. Fuel combustion produces most of the same carcinogens found in cigarette smoke, particularly polycyclic aromatic hydrocarbons, which are known animal carcinogens. Since all carcinogens are generally assumed not to have a threshold below which they have no effect, the carcinogenic characteristics of particles from combustion are assumed to be directly proportional to accumulated exposure.

Mortality

Mortality from exposure to particulate air pollution is attributable to increased susceptibility to infectious diseases and increased risk of heart failure from impaired lung function and the resulting inadequate oxygenation of the heart. "Killer fog" episodes involving extremely high concentrations of sulfur dioxide and acid particles have caused excess mortality for several days. Because of increased emission control requirements, these concentrations no longer occur outdoors in the United States, but they could be generated by indoor combustion of high-sulfur fuels. Excess mortality associated with cigarette smoking is also well documented.

Epidemiological studies consistently show relationships between excess mortality and outdoor particle concentrations in urban environments, but always in association with high concentrations of sulfur dioxide and other pollutants. Consequently, relationships with the direct casual agent or agents are not clear. Studies are further complicated by inadequacies in accounting for differences in other important variables such as smoking, weather, age, socioeconomic status, etc. Because of such methodological inadequacies, EPA considers most of these studies not useful for estimating quantitative dose-response relationships.

Sensitive Populations

A broad range of individuals is sensitive to the harmful effects of particle exposure. These include:

- Individuals with chronic obstructive lung diseases, such as bronchitis, bronchiectasis, and emphysema, are at special risk. Many of the excess deaths and illnesses following extreme air pollution episodes have occurred in this group.
- Individuals with cardiovascular disease have enhanced sensitivity to difficulties in breathing. Many of the deaths and hospitalizations during extreme air pollution episodes have occurred in this group.
- Individuals with influenza have increased sensitivity of the respiratory epithelium to any insult.
- Asthmatics have hypersensitive airways, especially to acids.

- The elderly have reduced lung elasticity and immunological deficiencies that make them less able to cope with additional insults. Many of the excess deaths and illnesses during extreme air pollution episodes have occurred in this group.
- Children are immunologically immature which makes them more susceptible to infection. There are suggestions that severe childhood respiratory infections may prevent lungs from reaching full development at maturity. Children are more active, have higher ventilation rates, and have higher particle deposition efficiencies than adults, thereby increasing dose of particles per unit body weight.
- Smokers have a higher base exposure onto which other pollutants add. Reduced ciliary and macrophagal clearance rates from smoking increase exposure to other particles.
- Individuals who routinely breathe through the mouth have increased penetration of particles deeper into the respiratory tract.

Many of these sensitivities occur jointly (e.g., smokers with chronic bronchitis) and they are causally interrelated (e.g., smoking can cause chronic bronchitis).

Interactions with Other Pollutants

The most important interactions of particles with other pollutants are related to increased exposures to all particles caused by the irritant effects of sulfur dioxide, NO_x , ozone, and acid particles themselves. Other interactions are related to the chemical reactions occurring in complex mixtures of particulate and gaseous pollutants. These reactions can increase and/or decrease the potency of the mixture. Discussion of these complex chemical relationships is beyond the scope of this handbook.

OTHER POTENTIALLY HARMFUL COMBUSTION PRODUCTS

This section discusses a few combustion products known to be potentially harmful to health, but produced in quantities too small to be of general concern in the indoor environment or produced only under unusual circumstances such that they are not of concern to the general population.

Sulfur Oxides

Sulfur dioxide is an irritant that has been shown to cause significant bronchoconstriction in the most sensitive of exercising asthmatics at concentrations as low as 260 microgram/cubic meter, which is within a factor of 2 of the upper limit of concentrations normally occurring in houses (see Section 5, Indoor Concentrations). Otherwise, sulfur dioxide has no known direct health effects on normal individuals at concentrations currently encountered in the United States. In general, it rapidly dissolves in water to form sulfurous acid,

which oxidizes to sulfuric acid, which in turn reacts with many substances to form particulate sulfates (See Table 2-1). Epidemiological studies consistently show relationships between exposure to sulfur dioxide and health effects related to reduced lung function, but these effects are not easily separable from those of sulfates and other particulate matter normally associated with high concentrations of sulfur dioxide.

In general, indoor concentrations of sulfur dioxide are about half of those outdoors. Fossil fuels from which combustion emissions are routinely discharged indoors (such as wood, natural gas, propane, and kerosene) do not contain much sulfur. High concentrations of sulfur oxides indoors are generally the result of accidents or misuse of equipment. These include leaky flues on oil-fired furnaces and burning of high-sulfur fuel oil in unvented kerosene space heaters. Most free-standing coal stoves burn anthracite coal, which has a low sulfur content. But, in areas where other types of coal are mined and available to the general public, the use of coal stoves may produce enough indoor sulfur dioxide emissions to cause health problems.

Except for the special circumstances mentioned above, sulfur oxides are not likely to be a health problem indoors. Consequently, they are not considered further in this document. Nonetheless, individuals potentially in these special circumstances are cautioned that sulfur oxides are among the most harmful of the various pollutants produced during combustion. Thus, care should be exercised to ensure that concentrations do not reach harmful levels.

Hydrocarbons

Most hydrocarbons have limited significance for human health at normal (non-industrial) indoor concentrations, except for their participation in the formation of photochemical smog (which may not be formed indoors). Important exceptions are aromatic hydrocarbons, including polycyclic aromatic hydrocarbons.

Aromatic hydrocarbons, particularly benzene, toluene, and xylene, can cause eye and nose irritation, and, in concentrations far above those attributable to combustion, can cause fatigue, weakness, confusion, and tingling skin. In chronic exposures, benzene can cause leukopenia, anemia, and chromosomal abnormalities. No human health effects have been reported for benzene or other unsubstituted aromatic hydrocarbons at concentrations normally occurring in the atmosphere.

Polycyclic aromatic hydrocarbons (PAH), including benzo(a)pyrene, benzanthracene, chrysene, benzofluoranthracenes, and indopyrenes, are among the most potent animal carcinogens known; all are thought to be carcinogenic in humans. The best-known of these, benzo(a)pyrene, is ubiquitous in the environment. In animals, it produces tumors closely resembling human carcinomas. These hydrocarbons rapidly condense to form particles or adsorb onto other particles; thus, in the environment, their health effects are inextricably bound to, and indistinguishable from, those of fine particles in general. Since the health effects of particles were discussed in detail above, hydrocarbons are not considered further as a separate class of pollution in this document.

Formaldehyde

A wide variety of aldehydes is produced during the combustion of organic fuels. Aldehydes can affect human health through their intrinsic toxic properties and through their ability to photo-decompose to free radicals that participate in smog formation (which may not occur indoors). Of the aldehydes produced during combustion, formaldehyde and acrolein are the most important to health. Both are powerful irritants. Formaldehyde is also carcinogenic in laboratory animals and presumed to be so in humans.

Although formaldehyde is an important indoor pollutant, contributions from combustion are relatively small compared to those from building materials such as plywood, particle board, fabrics, carpets, and insulating foams, all of which can contain formaldehyde-based resins. For this reason, formaldehyde is not considered further as a product of indoor combustion in this document.

Carbon Dioxide

The greenhouse effect of carbon dioxide has drawn much attention to potential future problems associated with large carbon dioxide emissions from fossil fuel combustion. Carbon dioxide is also known to have health effects at high concentrations. In the blood, carbon dioxide is important in regulating the breathing rate. Slight elevations in concentration produce an increase in breathing rate which increases transport of carbon dioxide from the blood out of the lungs. At higher concentrations, blood activity is affected which, in turn, affects many biochemical processes. Chronic elevation of carbon dioxide in the blood produces compensatory removal by the kidneys. The lowest concentration at which health effects (in guinea pigs) have been recorded is 3000 ppm. This concentration could be produced indoors by unvented space heaters, but in this case, the health effects of other pollutants would overwhelm those of carbon dioxide. For this reason, carbon dioxide is not considered in depth in this document.

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Section 3

EMISSIONS FROM COMBUSTION SOURCES

INTRODUCTION

There are numerous potential sources of combustion-generated pollutants in the indoor air environment. Table 3-1 presents a listing of the common pollutants which may be present in the indoor air, along with the potential sources of these pollutants.

TABLE 3-1. SOURCES OF COMBUSTION-GENERATED POLLUTANTS IN THE INDOOR AIR^a

POLLUTANT	SOURCES
Gas Phase Constituents	
Nitric oxide	Fuel combustion, tobacco smoking
Nitrogen dioxide	Fuel combustion, tobacco smoking
Carbon monoxide	Fuel combustion, tobacco smoking
Carbon dioxide	Fuel combustion, tobacco smoking
Sulfur dioxide	Fuel combustion
Water ^b	Fuel combustion
Radon ^c	Fuel combustion
Ammonia	Fuel combustion, tobacco smoking
Hydrogen cyanide	Fuel combustion, tobacco smoking
Formaldehyde	Fuel combustion
Acrolein	Tobacco smoking
Particulate Phase Constituents	
Nicotine	Tobacco smoking
Benzo(a)pyrene	Woodburning, tobacco smoking
Particulate matter	Fuel combustion, tobacco smoking
Phenol	Fuel combustion, tobacco smoking

^a Only common pollutants are shown in table.

^b Not a pollutant in the conventional sense; however, high levels of water vapor in indoor air may affect comfort and promote microbiological activity.

^c Radon has been found in small quantities in some natural gas, providing a potential source of indoor radon through fuel combustion. However, indoor radon concentrations are typically a result of sources other than fuel combustion.

Although the ambient air can in some cases be an important source of specific pollutants in the indoor air, pollutants generated by the operation of indoor combustion sources are generally more important in determining indoor air pollutant concentrations. One measure of the relative importance of a given indoor combustion source with regard to others is its *source strength*, or the rate at which pollutants are emitted to the indoor air during the operation of the combustion source.

The source strength of a given combustion source is a product of a number of factors, including:

- The amount of fuel consumed over a given time period by the combustion source, sometimes referred to as the *firing rate* or *fueling rate* of the combustion source.
- The amount of pollutants generated by the combustion source per unit of fuel consumed, referred to as its *emission rate*.
- The degree to which the products of combustion generated by the source are effectively vented to the outdoors, often referred to as the *degree of venting*.

Although the relative proportions of specific pollutants may vary, the total mass of indoor air pollutants generated by a given source over a given time period is directly dependent on the firing rate of the combustion source. Because of this phenomenon, different types of combustion sources (such as gas- or kerosene-fired space heaters) will typically have much higher source strengths in the home than other combustion sources (such as gas pilots) by virtue of their higher firing rates. Emission rate data provide useful information with regard to the amount of pollutants generated per unit of fuel consumed, which, in turn, is a good measure of the quantity of energy provided for a specific use (such as space heating). Thus, emission rate data can be useful in assessing the relative desirability of different combustion sources for a desired end use. For example, space heating may be provided in a home by many different designs of either gas- or kerosene-fired units. However, because of varying emission rates for the different designs and fuels, the amount and distribution of pollutants introduced into the indoor space by the different units, while achieving the same desirable rise in the indoor temperature, can vary dramatically.

The degree of venting is a dimensionless factor which expresses the effectiveness with which combustion-generated pollutants are diverted to the ambient air, a factor which may vary from zero percent (for unvented sources) to a theoretical one hundred percent effectiveness which may be approached by properly vented sources.

Of the factors which determine the source strength of a combustion source, perhaps the most important is the degree of venting, since emission and fueling rates are unimportant if the pollutants generated are vented to the outdoor air with one hundred percent effectiveness. Conversely, emission and fueling rates of combustion sources can be very important for sources which are unvented, either by design or by malfunction.

Combustion sources which are designed with and built into the home, such as natural gas- or oil-fired furnaces, are required by virtually all housing codes to be effectively vented to the outdoors. Consequently, although the emission rates from these combustion sources may be quite high, the source strength for vented combustion sources is generally expected to be negligible unless the venting systems for these combustion sources are designed or built improperly or otherwise become ineffective. Thus, the effectiveness of the venting system is much more important than emission rates for these types of combustion sources.

In indoor air quality studies, a distinction is usually made between the vented combustion sources discussed above and those sources which require some type of positive action by the user in order to ensure acceptable air quality in the indoor space in which they are operated. Combustion sources which generally have no provision for direct venting include kerosene space heaters, gas space heaters, and tobacco smoking. Although direct venting may generally be provided for wood heaters, fireplaces, gas stoves, and gas ovens, the effective venting of combustion products from these sources generally depends on positive actions by the user. Since the potential for mis-use of these combustion sources in the indoor environment is high, the real and potential indoor air quality impact of such sources is a common focus of indoor air quality research.

In this section, source strengths which have been measured by various researchers for portable gas- or kerosene-fired space heaters, woodstoves, fireplaces, gas-fired cooking ranges and ovens, and tobacco smoking under normal (and abnormal) conditions are tabulated. The purpose of this tabulation is to provide a basis for assessing the potential indoor air quality impact of different combustion sources which may be operated in a given home. Where possible, firing rates for each of these combustion sources have been listed so that emission rates may be calculated.

OVERVIEW OF COMBUSTION SOURCES, POLLUTANTS, AND SOURCE STRENGTHS

The rates at which pollutants are emitted from various sources are summarized in Table 3-2. This table includes common indoor sources and represents source strengths measured under a wide range of conditions. The studies reporting these source strengths are summarized in the following sections. References are provided for readers interested in more detailed information.

Important combustion-generated pollutants included in Table 3-2 are:

- Nitrogen oxides (NO_x)--When fuel is burned in air at high temperatures, many oxides of nitrogen may be formed (1). Concentrations of NO_x in indoor air are primarily affected by gas stoves, unvented kerosene and gas space heaters, and to a lesser degree, tobacco smoking. Woodstoves do not usually produce significant emissions of nitric oxide (NO) because of low flame temperatures (2). In the outdoor atmosphere, NO_x concentrations are highest in heavily populated, industrialized urban areas since fossil fuel combustion and vehicles are major outdoor sources of NO_x . Emissions of NO and nitrogen dioxide (NO_2) are often expressed as NO_x measured as total NO_2 .

TABLE 3-2. REPORTED SOURCE STRENGTHS FOR SELECTED COMBUSTION SOURCES

SOURCE	APPLIANCE TYPE	SOURCE STRENGTH (mg/hr)							BaP	Formaldehyde
		NO	NO ₂	CO	CO ₂	SO ₂	Particles ^a			
Kerosene Space Heaters ^b	Radiant	0.54-11	16-93 ^d	281-1,176	0.34 x 10 ⁶ 0.61 x 10 ⁶	31-144	0.13-0.19	-- ^c	--	0.66-6.2
	Convective	24-195	33-530 ^d	35-635	0.19 x 10 ⁶ 0.65 x 10 ⁶	37-144	<0.02-0.034	--	--	0.79-6.19
	Two-Stage	--	24-38.7	98.1-426.6	--	--	--	--	--	15.0-18.5
Gas Space Heaters ^b		1-4578	2-1225	12-25,000	0.21 x 10 ⁶ 2.35 x 10 ⁶	--	0.21-186	--	--	0.2-300
Gas Appliances ^f	Range (1 burner)	50-455	66-430	155-3,244	0.41 x 10 ⁶ 0.56 x 10 ⁶	1.29-1.66	3.8-30	--	--	8-23
	Oven	30-581	59.7-396	103-3,564	0.32 x 10 ⁶ 0.44 x 10 ⁶	0.67-1.09	0.118-0.126	--	--	20-28
Wood Heaters ^g		0.4-9.4	-2.8 ⁻⁷	11.9-2,136 ^d	--	--	2.5-230 ^d	2.0 x 10 ⁻³ 2.2 x 10 ⁻³	--	--
Tobacco Smoke ^h (1 cigarette per hr)	Sidestream plus mainstream (mg/ cigarette)	--	0.065-0.40	51.6-100	443	--	30-40	2.0 x 10 ⁻³	--	--
	Sidestream (mg/ cigarette)	2.78	0.8-0.73 ^d	21.0-105	143-555.5	--	10.8-19.5	1.4 x 10 ⁻³ 2.0 x 10 ⁻³	--	0.035-1

- ^a Particle size monitored varies
^b Based on references 9, 9, 10, 11, 12, 13, 22
^c Dash (--) indicates data not reported, or otherwise not available
^d NO_x emission rate reported as NO₂
^e Based on references 23, 24, 25, 26, 27, 28, 29, 30
^f Based on references 2, 3, 27, 30, 39, 40, 41, 43, 44
^g Based on references 45, 46, 48, 51
^h Based on references 5, 14, 30, 54, 55, 56, 57, 58, 60
ⁱ Negative (-) sign indicates net removal due to source operation
^j Large value during transient event measured.

- Carbon monoxide (CO)--CO is formed whenever fuel is incompletely burned. The CO concentration in the indoor atmosphere is mostly a result of combustion appliances such as gas stoves, portable kerosene and gas space heaters, and woodstoves. Tobacco smoking is a lesser source of CO (2). Outdoor CO, including emissions from vehicles in garages attached to homes, can also contribute somewhat to indoor CO levels.
- Carbon dioxide (CO₂)--Although the greatest contributor to the indoor concentration of CO₂ is normally metabolic activity, combustion sources also contribute significant quantities of CO₂. Gas stoves, portable kerosene heaters, and gas space heaters emit relatively large quantities of CO₂, while woodstoves and tobacco smoking produce smaller amounts (2).
- Sulfur dioxide (SO₂)--SO₂ is formed when fuels containing sulfur are burned. In the United States, indoor SO₂ is usually a result of infiltration of SO₂-polluted air from outdoor sources, primarily stationary fuel combustion and industrial processes. Transportation emissions contribute smaller quantities. The only significant potential indoor sources are portable kerosene space heaters and leaky flues in houses where sulfur-containing fuel oil is burned.
- Respirable suspended particular matter (RSP)--Tobacco smoke is the primary contributor to indoor concentrations of RSP (<3.5 microns diameter). However, woodstoves and gas burners can also contribute RSP to the indoor environment, while gas ovens and kerosene and gas heaters contribute relatively small amounts of RSP (2,3). Generally, RSP concentrations are lower outdoors than they are indoors (2,4).
- Benzo(a)pyrene (BaP)--Indoor concentrations of BaP are a result of wood combustion and tobacco smoking.
- Formaldehyde--Most sources of formaldehyde, a gaseous organic compound, are found indoors. The major sources of formaldehyde are particle board, plywood, furnishings, carpets, and urea-formaldehyde foam insulation. Less significant sources of formaldehyde are combustion products from gas stoves, woodstoves, gas and kerosene heaters, and tobacco smoke. Levels of formaldehyde in the ambient air are relatively low.

In addition to the most commonly discussed pollutants, a number of trace contaminants have been identified in emissions from residential combustion sources. For example, a number of gases, vapors, and particles have been identified in mainstream and sidestream tobacco smoke. Various trace pollutants

are also emitted from residential wood-fired stoves. Radon has been found in small quantities in natural gas, resulting in estimated concentrations in residences due to gas combustion of less than 0.1 nanocuries per cubic meter (5). Bruno reported that natural gas and propane at the wellhead frequently contain significant amounts of radon, but the long distribution time to the point of use leads to a manifold reduction in radon concentration (6). Natural gas will be a potentially significant radon source only where a house is located close to the wellhead and burns a great deal of gas without venting the combustion products.

Although hundreds of pollutants may be identified in the indoor atmosphere, this handbook will focus on the more commonly discussed combustion-generated pollutants found in indoor air. Pollutant emissions vary widely among combustion sources, depending largely on the type of fuel used, the type of appliance, and the manner of operation. These factors will be discussed in the following sections covering common sources of combustion-generated pollutants indoors.

KEROSENE HEATERS

Kerosene heaters can have high indoor source strengths, mainly because they are generally operated in an unvented manner. In most cases, the source strengths of the various pollutants generated by kerosene heaters are equal to their emission rates, which, in turn, depend to a large degree on the amount of heat provided or fuel consumed. Portable kerosene space heaters contribute to elevated indoor levels of CO, CO₂, NO, NO₂, SO₂, RSP, and formaldehyde. The rate of emission of each of these pollutants is dependent on a number of factors, including the following:

- Usage pattern or firing rate
- Manufacturer and type of heater (convective, radiant, or wickless)
- Wick adjustment
- Fuel type
- Age of heater.

The brand and type of heater used will also affect the rates of emission of the various pollutants. There are basically five types of heaters on the market today: radiant, convective, radiant/convective, two-stage, and wickless. Heaters may also be characterized as blue-flame or white-flame heaters, depending on the color of the flame, which is determined by the burner design, the manner in which air enters the burner area, and the temperature of the flame. For example, a white flame burns hotter than a blue flame.

Radiant heaters generally have a rectangular base and are open at one side. A metal reflector beams out infrared heat from the burner without heating the air itself. Most units, which are generally blue-flame, are rated by their manufacturers at 6,000 to 10,000 Btu/hr and are designed to operate at essentially constant heat output except for some wickless models.

Convective heaters are generally cylindrical in shape. Slots at the base surround the burner and draw in cool air, which is heated by a flame. The air

then moves out through slots at the top of the unit and sets up a convection current that distributes heat through a room. Most convective models are rated at about 12,000 to 20,000 Btu/hr, according to the manufacturers. Convective heaters can be blue-flame or white-flame, depending on the design of the burner used.

Radiant/convective heaters, which are generally blue-flame, have a reflector behind the burner, as well as a configuration that provides dispersion of warm air in all directions.

Two-stage kerosene heaters, which appear to have fewer emissions than other types of kerosene heaters, have recently become available in the United States. Incorporating features of convective and radiant kerosene heaters, two-stage kerosene heaters provide for more complete combustion of the kerosene fuel through the use of a dual burner design.

Wickless heaters, which are generally rated at 5,000 to 19,000 Btu/hr, contain a chamber in which fuel and air mix and combustion occurs. An electric fan then distributes the heat outward. Some wickless heaters have a built-in thermostat that maintains the desired temperature in the room by increasing or decreasing the rate of combustion automatically.

Although the basic combustion process for heaters with wicks is similar to that for wickless heaters, the adjustment of the wick on a portable kerosene heater will influence pollutant emission rates. A wick is immersed in kerosene, and when it is extended above the kerosene level, it can be ignited by flame or electric ignition. Flame height can be controlled by using an adjustment knob. Most manufacturers specify only one flame or burner condition as correct, although some manufacturers' models do have wick height adjusters intended to control heat output. Typically, instructions for heaters state that one should light the heater with the wick set high, then lower the wick until the flame takes on a specified size or shape. A flame which is too high or too low can cause soot formation, odor, and excessive CO production due to incomplete fuel combustion.

The quality of the kerosene fuel will also affect the pollutant emission rate. The sulfur present in kerosene, though small in amount, reacts with oxygen to form SO_2 in the combustion process. Kerosene fuel is produced by approximately 33 domestic companies. Kerosene manufactured to the American Society for Testing and Materials Specification D3699 Grade No. 1-K has no more than 0.04 percent by weight of sulfur and Grade No. 2-K has no more than 0.30 percent by weight of sulfur. Very few companies market a certified or specifically labeled 1-K kerosene. The Consumer Product Safety Commission reported that the average kerosene available to the consumer for indoor use has a sulfur content slightly higher than the 1-K specification (7). Consumer Reports suggested that 1-K is the appropriate fuel to use in kerosene heaters because using 2-K will dramatically increase SO_2 emissions and can gum up the wick in a heater (1). However, finding the recommended fuel is not always easy because of limited distribution of the 1-K fuel.

Table 3-3 summarizes measured source strengths of kerosene heaters. In general, the data show that NO_x emissions are higher and CO emissions are lower with convective heaters. The adjustment of the flame on the heater has been

TABLE 3-3. REPORTED SOURCE STRENGTHS OF KEROSENE HEATERS

STUDY	APPLIANCE TYPE	SOURCE STRENGTH (mg/hr)						
		NO	NO ₂	CO	CO ₂	SO ₂	RSP	FORMALDEHYDE
Leaderer 1982 (8)	Radiant (9,600 Btu/hr) ^a normal flame high flame low flame	0.54	33.7	393	453,000	109	-- ^b	--
		3.90	38.0	366	612,000	144	--	--
		--	29.8	399	344,000	91	--	--
	Convective (8,700 Btu/hr) ^a normal flame high flame low flame	68.6	85.2	131	421,000	94	--	--
		156.6	66.0	96	652,000	144	--	--
		23.9	38.5	58	186,000	40	--	--
Traynor 1982, 1983 (9,10)	Radiant (7,760 Btu/hr) ^c new unit, normal flame new unit, low flame old unit, normal flame	10.7	38.2	542	570,000	--	0.16 ^d	4.60
		3.34	37.1	864	528,000	--	0.19	5.12
		3.9	33.9	359	440,000	--	0.13	0.66
	Convective (7,430 Btu/hr) ^c new unit, normal flame new unit, low flame old unit, normal flame	194.9	101.8	85	559,000	--	<0.03	0.79
		76.6	105.8	359	330,000	--	<0.02	1.78
		61.9	178.2	635	373,000	--	0.034	6.19
Yamanaka, et al. 1979 (11)	Radiant (7,979 Btu/hr) ^c	•	92.6 ^e	--	--	--	--	--
	Convective (8,372 Btu/hr) ^c	•	529.9 ^e	--	--	--	--	--
Jones 1983 (12)	Radiant (9,600 Btu/hr) ^a new unit old unit	--	16	281	--	31-38	--	--
		--	16-25	457-539	--	48	--	--
	Convective (11,500 Btu/hr) ^a new unit	--	33-53	35-77	--	37-61	--	--

TABLE 3-3. REPORTED SOURCE STRENGTHS OF KEROSENE HEATERS (CONTINUED)

STUDY	APPLIANCE TYPE	SOURCE STRENGTH (mg/hr)						RSP	FORMALDEHYDE
		NO	NO ₂	CO	CO ₂	SO ₂			
Traynor, et al. 1986 (13)	Radiant (6,600 Btu/hr) well tuned	3.71-5.95	32.2-35.7	553-644	--	--	--	--	--
	Convective well tuned	126-133	41.3-53.2	126-161	--	--	--	--	--
Apte, et al. 1986 (22)	Convective, fully on 11,020 ± 5,035 Btu/hr	--	99.8	139.2	--	--	--	--	--
	Convective, partially on 7,410 ± 4,750 Btu/hr	--	124.8	468	--	--	--	--	--
	Radiant, fully on 8,455 ± 2,090 Btu/hr	--	40.9	605.2	--	--	--	--	6.2
	Radiant, partially on 6,460 ± 1,045 Btu/hr	--	37.4	1,176.4	--	--	--	--	3.4
	Two-Stage, fully on 10,355 ± 4,560 Btu/hr	--	24.0	98.1	--	--	--	--	18.5
	Two-Stage, partially on 7,505 ± 1,425 Btu/hr	--	38.7	426.6	--	--	--	--	15.0

^a Manufacturers rated output for unit.

^b Dash (--) indicates data not reported or otherwise not available.

^c Measured fuel consumption.

^d Mass of particles from 0.005 to 0.4 microns in diameter analyzed using an electrical mobility detector assuming particulate density of 2.0 g/cm³.

^e NO_x emissions reported. NO was converted to equivalent NO₂.

shown to influence emission rates. A higher-than-normal flame will increase NO emission rates while a lower flame increases CO, formaldehyde, and particle emission rates. Most studies determined that SO₂ emission rates were dependent on the sulfur content of the fuel and were not significantly affected by changes in the flame or the type and age of the heating unit. It has also been determined that there is no significant difference in emissions with or without a warm-up period.

The age and condition of a portable kerosene space heater will also affect its pollutant emission rates. Maintaining and cleaning a heating unit and operating the unit according to manufacturer's specifications is essential to minimizing pollutant emissions. Table 3-4 summarizes the impacts of various factors on the emissions from kerosene space heaters.

Leaderer measured air pollutant emissions from a portable convective and a radiant kerosene space heater in an environmental chamber (8). The radiant-type heater was rated at 9,600 Btu/hr and the convective-type heater at 8,700 Btu/hr. The kerosene used was purchased locally; however, fuel grade was not indicated. The air pollutant emission rates (milligrams of pollutant per gram of fuel consumed) were measured for both heaters operated at three different wick settings: the one recommended by the manufacturer, a high setting that gave a high flame, and a low setting that gave a low flame. When the concentrations of contaminants reached a steady-state in the chamber, these concentrations and the fuel consumption rate were recorded and emission rates were calculated. The resulting emissions are given in Table 3-3. The following observations were made concerning the measured emissions from these experiments:

- NO₂ emission rates are considerably higher for the convective heater than for the radiant heater.
- NO_x emissions for the radiant heater are almost entirely in the form of NO₂, while NO and NO₂ emissions from the convective heater are similar.
- Variations in fuel consumption rate had little effect on NO₂ emission rates for the radiant heater, while a high fuel consumption rate in the convective heater lowered the NO₂ and increased the NO emission rates.
- SO₂ emission rates for both heaters at all fuel consumption rates are about equal. The emission rates of SO₂ correspond to a fuel with a sulfur content of about 0.035 percent, typical for the Grade 1-K kerosene.
- CO emission rates were found to be higher for radiant heaters due to less efficient combustion.

Traynor, et al. conducted laboratory tests on two radiant and two convective portable space heaters to measure emissions and emission rates (9,10). Tests were conducted in a 27-cubic-meter (m³) environmentally controlled

TABLE 3-4. INFLUENCE OF OPERATING FACTORS ON THE OBSERVED POLLUTANT EMISSION RATES FROM KEROSENE SPACE HEATERS

FACTOR	EFFECT
Manufacturer and Type of Heater	
Manufacturer or Model	<ul style="list-style-type: none"> • Some heaters have significantly higher emission rates than other brands or models of the same type (15,17) • Considerable variability in emission rates which are not associated with heater type or manufacturer Btu rating (15)
Convective Versus Radiant	<ul style="list-style-type: none"> • NO_x emissions from radiant heaters contain mostly NO_2; similar NO and NO_2 content in NO_x emissions from convective heaters (8) • Higher NO_2 emissions from convective heaters relative to radiant heaters (8) • No differences in SO_2 emissions between the two heater types; higher CO emissions for radiant heaters due to less efficient combustion (8) • Convective heaters emit lower CO, but significantly more NO_2 (20) • Convective heaters produced 2-9 times the elemental carbon; heater type and use affected organic emissions more than those of other pollutants (15) • Increased NO_x emissions from convective heaters; higher CO, formaldehyde, and fine particle emissions from radiant heaters (9,10)
Blue Versus White Flame	<ul style="list-style-type: none"> • Blue flame heaters generated NO_2 at half the rate and CO at five times the rate of white flame heaters (20)
Ambient Air	<ul style="list-style-type: none"> • Increased CO emissions from blue flame heaters with lower oxygen content of ambient air (15)
Wick Adjustment	<ul style="list-style-type: none"> • Increased CO and formaldehyde emission rates, but no effect on particulate emissions for new convective heaters with shorter wick adjustments; small increases in CO and formaldehyde emissions for radiant heaters (9,10) • Increased CO emissions (by a factor of 2-4) with wick readjustment (20).
Fuel Type	<ul style="list-style-type: none"> • SO_2 emissions dependent on the sulfur content of fuel (8,20)
Fuel Consumption Rate	<ul style="list-style-type: none"> • Little effect on NO_2 emissions from radiant heaters; high fuel consumption lowered NO_2 and increased NO emissions from convective heaters; while low fuel consumption increased CO emissions from radiant heaters (8) • Increased CO emissions from radiant heaters with reduced fuel firing rate (15)
Heater Age	<ul style="list-style-type: none"> • Possible increase in fine particle emissions with increased age (9,10) • Significantly higher CO, NO_2, and particle emissions but less SO_2, CO_2, and NO emissions from a five-year-old heater relative to a new heater of the same size (16)

chamber. Fuel consumption rates were measured at 7,760 Btu/hr for the radiant heaters and 7,430 Btu/hr for the convection heaters. The masses of particles from 0.005 to 0.4 microns in diameter were analyzed using an electrical mobility detector assuming particulate density of 2.0 grams/cubic centimeter (g/cm^3). The resulting emissions from twelve tests are summarized in Table 3-3. The following observations were made:

- All four heaters were found to emit CO, CO₂, NO, NO₂, and formaldehyde, and both radiant heaters and one convective heater emitted fine particles.
- The CO₂ production rates and oxygen consumption rates were relatively constant for both types of heaters.
- NO_x emission rates were greater for convective heaters, and CO, formaldehyde, and fine particles were greater for radiant heaters. It was suggested that the difference was due to the hotter flame in convective heaters.
- No significant difference in emission rates was found with and without a warm-up period except with the 5-year-old convective heater which, upon ignition, initially emitted 440 micrograms (μg) of fine particles (seen as a burst of smoke).
- Adjusting the wick length affected pollutant emissions in that the maximum wick extension produced the best burning conditions. Reducing the wick extension until the flame was half its original length for the new convective heater reduced the fuel consumption rate but increased the CO and formaldehyde emission rates by factors of 8 and 4, respectively, but had no effect on fine particulate emissions. The new radiant heater wick was reduced, resulting in an increase in CO emissions with the decrease in fuel consumption, but only a slight increase in formaldehyde and fine particle emissions.

The experimental studies conducted by Yamanaka, et al. and Weston involved monitoring emission rates by using a hood placed over heating units (11,12). Yamanaka, et al. conducted an experimental study of 11 kerosene space heaters (11). Combustion gas was collected from a duct with a hood under which each unit was operated with a flame adjusted according to manufacturers' specifications. The combustion gas was drawn by a fan, with a controlled amount of air, to insure that all of the combustion gas passed into the duct for sampling. Tests included fifteen runs with a radiant heater and ten runs with a convective heater. The amount of NO₂ produced per unit of fuel was used as the unit of the emission factor of NO_x, where NO was converted to equivalent NO₂. The NO emissions measured were always extremely low. The results are given in Table 3-3. The observation was made that the blue-flame convective heater resulted in an NO_x emission rate of several times that of the radiant heater, which had a metal screen in the flame.

Weston tested three heaters: a new radiant heater (9,600 Btu/hr rated output), an identical used radiant heater, and a new white-flame convective heater rated at 11,500 Btu/hr (12). Emission rates were measured in an occupied dwelling using a hood placed over the heating unit. The data showed that emission rates of CO, NO₂, and SO₂ were higher with the old radiant heater than the new unit. The kerosene used throughout the tests had a sulfur content of 0.02 percent and resulted in SO₂ source strengths of 31 to 61 mg/hr. NO₂ emissions were highest with the convective unit and CO emissions were lowest.

Traynor, et al. studied emissions from kerosene heaters in a 27 m³ chamber and reached the following conclusions (13):

- Previous studies on the emissions from kerosene heaters were confirmed in that these appliances can emit polycyclic aromatic hydrocarbons (PAHs) and nitrated PAHs.
- A range of aliphatic hydrocarbon pollutants is emitted from these appliances, including alcohols, ketones, phthalates, and alkyl benzenes. Pentachlorophenol was also observed, but mechanisms for its production were not understood.
- Some estimates of the indoor reactivity of semi-volatile organic compounds (SVOCs) were higher than 2 per hour. This was inferred to imply that reactivity rates for some SVOCs are more important than ventilation rates for determining indoor concentrations.

The last conclusion from this study indicated that future studies must quantify the indoor reactivity process for individual SVOCs in order to gain insight into potential indoor exposures to these compounds.

Girman, et al. conducted experiments with a convective-type unvented kerosene space heater in an environmental chamber under controlled ventilation (14). The manufacturer reported an output of 8,200 Btu/hr; however, the consumption rate, based on the theoretical CO₂ emission and observed CO₂, was 6,200 Btu/hr. Gas pollutant concentrations were measured and emission rates were then calculated. As a result of these tests, the researchers concluded that CO₂, NO, and NO₂ emissions were significant; however, the CO emissions were relatively low and particle concentrations were near background levels.

Kweller and Cuthrell tested three portable kerosene space heaters supplied by the Consumer Product Safety Commission to determine the amount of CO that can be expected in a home using these heaters (15). One heater (I) was designed to operate only at maximum fuel rate, measured at 10,464 Btu/hr. The second heater (II) was a blue-flame-type heater with a rated heat output of 5,870-9,329 Btu/hr. The third heater (III) was a radiant-type heater with a rated output of 7,100-7,500 Btu/hr. The tests were conducted in a test room with controlled temperature, ventilation, and oxygen level. The test room air was analyzed for CO, CO₂, and oxygen. Tests results were obtained after adjusting the heaters' firing rate in accordance with the operating instructions. Steady-state room

oxygen conditions were determined to be 18.5-19.6 percent. CO concentrations ranged from 10 to 98 parts per million (ppm). This study identified some factors which influence CO emissions:

- Heaters I and II showed a trend of increasing CO emissions with reduced oxygen levels in the room.
- The kerosene heater's flame size diminished as the oxygen level was reduced. In some tests, the flame was reduced to half its original size. This was more noticeable with Heaters I and II. This characteristic made it impossible to operate the heaters in the test room at their maximum ratings, resulting in poor combustion. The cutback in firing rate for the radiant heater produced an increase in CO level.

Ritchie and Oatman conducted a study on air pollution from three different convective kerosene heaters in a townhouse (16). The heaters were fueled with kerosene containing less than 0.1 percent sulfur, which was marked as being suitable for use in unvented heaters. Wick adjustments were made in accordance with the manufacturer's recommendations, and pollutant concentrations were measured before, during, and after heater operation. Resulting pollutant concentrations were reported and are discussed in Section 5, Indoor Concentrations. This study resulted in some findings related to effects of the age of heaters on emissions:

- A five-year-old heater resulted in CO, NO₂, and particle concentrations that were twice as high as those from a new heater of the same size.
- The older heater produced less CO₂, NO, and SO₂. These differences could be due to wick deterioration or burner design, both of which can affect combustion efficiency.

Consumer Reports tested 18 different models of kerosene heaters (1). Thirteen of these were radiant heaters rated by their manufacturers at 9,000 to 10,000 Btu/hr; however, during the tests they delivered only about 7,000 Btu/hr. The other five heaters were convective types which were rated at 15,000 to 20,000 Btu/hr, but they actually delivered 13,000 Btu/hr. Average concentrations of CO, CO₂, NO₂, and SO₂ were calculated based on tests conducted by the Lawrence Berkeley Laboratory and the Pierce Foundation Laboratory as well as their own findings. As a result, the following observations were made:

- Only small differences in pollutant emission rates were found for a given type of heater (convective or radiant).
- The convective heaters produced much lower CO levels than the radiant heaters.
- NO₂ emissions were far higher from the convective heaters than the radiant heaters.

Efforts to reduce levels of the classical combustion emissions (CO , CO_2 , NO_x , and SO_2) have resulted in new unvented kerosene heater designs. The effects of these new designs on such emissions, as well as particle and organic emissions, were investigated by Boone, et al. and White, et al. (17,18,19). In the first phase of a three-phase study, emissions from 12 heaters, covering a range of design types and Btu ratings, were evaluated during start-up and three steady-state operating conditions (normal, low, and high flame settings). Aerosol mass, size distribution, extractable mass, bioassay and trace element content as well as conventional gas (CO , NO_x , etc.) measurements were made for all the heaters tested, while volatile organic compounds (VOCs) and semi-volatile measurements were made for a subsample of the heaters. Phase II characterized gas and particle emissions from four heaters representing the four types tested in Phase I: the traditional convective and radiant heaters, as well as two two-stage heaters. Phase III consisted of a series of heater runs in the EPA test house in North Carolina. The test house experiments were designed to validate model predictions based on the chamber studies in Phase II. Observed pollutant level ranges from this study are listed in Table 3-5.

Observations and conclusions from this study included the following:

- Unvented kerosene space heaters are a significant source of indoor RSP.
- There was considerable variability in the emissions that was not associated with heater type or manufacturer Btu rating.
- Heater type and use affected the composition and amount of organic emissions more than CO , CO_2 , NO_x , SO_2 , or inorganic particle emissions.
- Aerosol carbon content varied from 5-47 percent with elemental carbon accounting for 3.5-30 percent of the carbon.
- Convective-type heaters produced 2-9 times more elemental carbon than radiant-type heaters.
- The test house and mobile home test scenarios demonstrated that unvented kerosene heaters can be significant sources of respirable suspended solids.

The Consumer Product Safety Commission (CPSC) reported on the results of kerosene heater studies (20). The results of these studies are reported and discussed as concentrations resulting from use of kerosene heaters and are discussed further in Section 5, Indoor Concentrations. The following observations related to pollutant emissions were made as a result of their evaluation:

- CO and NO_2 are the major pollutants of concern for blue-flame heaters.
- NO_2 is the major pollutant for white-flame and wickless heaters.

TABLE 3-5. SUMMARY OF PARTICLE EMISSIONS FROM KEROSENE HEATERS

KEROSENE HEATER TYPE ^a	RATED OUTPUT BTU/HR ^b	TOTAL MASS ^c ($\mu\text{g}/\text{m}^3$)		PARTICLE VOLUME ^d ($\mu\text{m}^3/\text{cm}^3$)			ESTIMATED EMISSION RATE ^e ($\mu\text{g}/\text{g}$)
		PERSONAL PUMPS	PM10	NORMAL	LOW	HIGH	
R	9,300	130	63	47	33	38	62
R	9,300	104	46	50	67	58	44
R	10,500	201	133	102	71	100	80
R ^f	12,500	73	--	109	56	102	25
R ^f	12,500	166	69	72	70	40	44
R	12,500	151	65	136	70	122	56
R/R ^g	12,600	533	--	342	211	299	175
R/R ^g	12,600	721	269	812	643	1097	260
C	8,200	79	33	45	18	52	20
C	12,700	148	85	137	147	214	47
C	17,100	188	86	45	48	46	59
C/R ^h	9,400	91	63	74	28	89	54
C/R ^h	9,400	98	47	50	26	53	53
C/R	17,500	132	75	100	66	138	27

^a R (radiant), R/R (double radiant), C (convective), and C/R (combination)

^b BTU output as advertised by manufacturer

^c Total mass was collected from 4 to 7 personal pumps (3 liter/min) spread throughout the chamber and a PM10 sampler (100 liters/min) without the head

^d Volume is calculated from the EPA particle size data (0.01 - 1.0 microns). The buildup particle volume is the largest volume calculated (two minute size distribution measurement) during the period of heater startup to normal steady-state. The normal, low, and high volumes are the average of fifteen two-min size distribution measurements taken during steady-state air contaminant concentrations associated with normal, low and high fuel burning conditions.

^e Calculated from personal pump mass, fuel consumption, and effective removal

^f Same heater with different fuels (one--0.06 percent sulfur, 0.002 percent ash and two--0.02 percent sulfur, 0.016 percent ash)

^g Same heater, duplicate runs

^h Same heater model (first one is new and second one is old)

Source: Boone, P.M., et al., "Chamber Studies Characterizing Organic Emissions From Unvented Kerosene Space Heaters: Phase II," presented at the 1988 EPA/APCA Symposium on Measurement of Toxic and Related Air Pollutants, Raleigh, North Carolina, May 4-6, 1988.

- Blue-flame heaters generated NO_2 at about half the rate of white-flame heaters.
- The blue-flame heaters produced CO at almost five times the rate of white-flame heaters.
- Maladjustment of wick height resulted in a two-fold to four-fold increase in the production of CO.
- SO_2 emissions do not appear to be related to heater type but rather to the sulfur content of the fuel used and the amount of fuel used.
- Some heaters have significantly higher emission rates than other brands or models of the same type.

J. M. Dave studied the effects of operating pressure-type kerosene stoves on the pollutant levels in small kitchens (21). The emission rates of pollutants were measured on a per liter of kerosene consumed basis. The results generated from this study are shown in Table 3-6. The data show that pressure stoves release "exceptionally high" levels of pollutants, and that the release of pollutants at these rates in unventilated kitchens elevates pollutant concentrations to unsafe levels. The importance of reducing sulfur contents of kerosene fuels used in these appliances to less than 0.1 percent was stressed.

Apte, et al. investigated emission rates from convective, radiant, and two-stage kerosene space heaters (22). Pollutant emission rates for CO, CO_2 , NO, NO_2 , formaldehyde, and submicron suspended particles were measured. Pollutant measurements were made in a 27 m^3 environmental chamber, and emission rates were calculated using a mass-balance model. It was observed that:

- Burner design was the most important characteristic in determining the relative amounts of pollutants emitted.
- The two-stage heaters exhibited lower CO and NO_2 emissions per unit of fuel consumed than the convective or radiant kerosene heaters.
- The radiant kerosene heaters emitted the highest amount of CO per unit of fuel consumed.
- The convective heaters emitted the most NO_2 per unit of fuel consumed.
- All of the kerosene heaters were found to emit more CO and NO_2 on average when operated with lowered wicks.

GAS SPACE HEATERS

The use of unvented gas-fired space heaters can contribute to indoor levels of CO, CO_2 , NO, NO_2 , RSP, and formaldehyde. The emission rates of these pollutants will vary, depending on a number of factors including the following:

TABLE 3-6. EMISSION RATES FOR KEROSENE PRESSURE STOVE^{a,b}

CONSTITUENT	EMISSION, mg/liter OF KEROSENE		COMMENTS
	WITH PAN	WITHOUT PAN	
NO	23.6	32.40	Normal cooling with pan; rate of fuel: 280 gm/hr
NO ₂	42.8	61.56	
CO	458.3	341.08	
SO ₂	3560.0	3740.00	
BaP	3.8	3.10	
CO ₂	1807.0	1807.00	3 minutes lighting; 9-20 gm fuel
Particles	780.0	780.00	

^a Calorific value of kerosene: 3,200 Btu/lb

^b Sulfur content of kerosene: 0.25 percent by weight.

Source: Dave, J.M., "Emissions from Conventional Kerosene Stove Used In Indian Kitchen," n.d.

- Usage pattern
- Brand of heater and burner design
- Size of heater (rated input)
- Tuning of fuel-to-air mixture.

As with kerosene space heaters, gas heaters are used during the cold months of the year for a number of hours during the day, resulting in emissions over a relatively long period of time. There are a wide variety of heater types available on the market.

Experimental studies have been conducted to investigate pollutant emission rates and the factors which influence these rates. The influence of various factors on the emissions of gas space heaters is described in Table 3-7 with quantitative information summarized in Table 3-8.

TABLE 3-7. INFLUENCE OF OPERATING FACTORS ON THE OBSERVED POLLUTANT EMISSION RATES FROM GAS-FIRED SPACE HEATERS

FACTOR	EFFECT
Vented or Unvented Design	<ul style="list-style-type: none"> No statistical difference (23)
Fuel Input Rate	<ul style="list-style-type: none"> Increased CO and NO₂ emissions and decreased NO and total NO_x emissions as fuel input rate is decreased below normal (23,24,25,26)
Convective Versus Infrared Types	<ul style="list-style-type: none"> Lower NO_x emissions from infrared heaters (26)
Presence of Radiant Ceramic Tiles	<ul style="list-style-type: none"> Increased NO_x emissions (23)
Usage	
High flame conditions	<ul style="list-style-type: none"> Increased CO, NO, and NO₂ emission rates (27)
Primary aeration rate (poor tuning indicated by yellow-tipped flame)	<ul style="list-style-type: none"> Decreased NO, slightly higher NO₂, and increased CO and CH₄ levels when poorly tuned (23) Slightly higher CO emissions (24,25,26)
Burner Designs	
Single port versus multiport	<ul style="list-style-type: none"> Lower NO_x emissions from single port types relative to multiport units (23) Reduced NO_x levels (23)
Presence of screen in flame	
Time	<ul style="list-style-type: none"> Stable CO, NO, and NO₂ rates for infrared space heaters; CO emission rates variable by up to 50 percent over time for convective space heaters (25,26)
Fuel Type	<ul style="list-style-type: none"> No difference for propane or natural gas (30)
Emission Rate Measurement Method	<ul style="list-style-type: none"> For blue-flame heaters, good agreement for NO₂ emissions, but poor agreement for NO and CO between hood, chamber, and probe methods under uncontrolled circumstances (28) For gas-fired infrared heaters, poor agreement between hood, chamber, and probe methods under uncontrolled circumstances (28) Chamber method can result in unrealistically high CO emission rates (28,29)

TABLE 3-8. REPORTED SOURCE STRENGTHS OF GAS-FIRED SPACE HEATERS

STUDY	OPERATING CONDITIONS	SOURCE STRENGTH (mg/hr)						RSP	FORMALDEHYDE
		NO	NO ₂	CO	CO ₂				
Cote, et al. 1974 (27)	Low flame, steady-state, 11,100 Btu/hr	214	130	1770	--	--	--	--	--
	High flame, 24,600 Btu/hr	837	272	1982	--	--	--	--	--
Thresher and DeWorth 1979 (23)	Vented	1562	187	493	--	--	--	--	29
	Average								
	Range	317-4578	<3-1225	12-5004	--	--	--	--	0.2-300
	Unvented	865	143	122	--	--	--	--	4.1
	Range	183-2009	26-331	23-315	--	--	--	--	4.1
Trenor, et al. 1983 (24,25)	Well tuned, full input, laboratory	249-817	199-912	319-2954	0.50 x 10 ⁶ - 2.35 x 10 ⁶	0.21-3.23	0.21-3.23	13.7-42.9	
	Average	521	390	1212	1.47 x 10 ⁶	1.31	1.31	23.8	
	Well tuned, partial input, laboratory	81-373	51-230	71-835	0.21 x 10 ⁶ - 1.36 x 10 ⁶	<0.026- 0.264	<0.026- 0.264	0.39-30.6	
	Average	203	150	289	0.78 x 10 ⁶	<0.093	<0.093	11.78	
	Well tuned, house								
	Average	899	235	339	--	--	--	--	--
	30,000 Btu/hr Manufacturer A	709	325	777	--	--	--	--	--
	Initial	805	191	369	--	--	--	--	--
	Final								
	30,000 Btu/hr Manufacturer C	905	231	374	--	--	--	--	--
	Initial	752	374	468	--	--	--	--	--
	Final	830	137	259	--	--	--	--	--
16,000 Btu/hr Manufacturer B	Average	384	299	3143	--	--	--	--	--
	Initial	273	308	2931	--	--	--	--	--
	Final	318	271	3070	--	--	--	--	--
12,000 Btu/hr Manufacturer A	Average	230	82	304	--	--	--	--	--
	Initial	80	181	1236	--	--	--	--	--
	Final	257	66	47	--	--	--	--	--
Excess fuel, house 30,000 Btu/hr Manufacturer A	Average	677	282	1163	--	--	--	--	--
	Initial	508	365	2861	--	--	--	--	--
	Final	604	224	1132	--	--	--	--	--

TABLE 3-8. REPORTED SOURCE STRENGTHS OF GAS-FIRED SPACE HEATERS (CONTINUED)

STUDY	OPERATING CONDITIONS	SOURCE STRENGTH (mg/hr)						FORMALDEHYDE
		NO	NO ₂	CO	CO ₂	RSP		
Traynor, et al. 1983 (24,25) (continued)	Excess air, house							
	30,000 Btu/hr Average	<3	638	19778	--	--		--
	Manufacturer A Initial	<3	309	24882	--	--		--
	Final	<3	670	18821	--	--		--
Traynor, et al. 1984 (26)	Well-tuned, full input, infrared							
	• Natural gas Initial	<2-16	66-94	723-1391	--	2-8		8-19
	Final	<2-22	86-119	606-1307	--	2-11		10-15
	• Propane Initial	2	74	697	--	2		14
	Well-tuned, full input, infrared							
	• Natural gas Initial	572	281	820	--	19		4
	Final	519	376	837	--	186		9
	• Propane Initial	506-898	275-398	289-1007	--	2-3		1-6
	Final	577-1060	249-460	410-557	--	7-20		9-17
Institute of Gas Technology 1986 (28,29)	Manufacturer A, 10,000 Btu/hr, blue flame, natural gas	102-187	89-115	104-350	--	--		--
	Manufacturer B, 15,000 Btu/hr, blue flame, natural gas	173-343	133-164	232-657	--	--		--
	Manufacturer C, 15,000 Btu/hr, infrared, natural gas	1-9	29-55	1091-1383	--	--		--
	Manufacturer D, 17,300 Btu/hr, infrared, natural gas	3-22	33-69	216-346	--	--		--
	Manufacturer E, 40,000 Btu/hr, blue flame, LPG	1193-1680	321-336	154-232	--	--		--
	Manufacturer F, 20,000 Btu/hr, blue flame, LPG	671-936	171-222	116-356	--	--		--
	Manufacturer G, 30,000 Btu/hr, blue flame, natural gas	167-413	600-738	6400-14123	--	--		--

TABLE 3-8. REPORTED SOURCE STRENGTHS OF GAS-FIRED SPACE HEATERS (CONTINUED)

STUDY	OPERATING CONDITIONS	SOURCE STRENGTH (mg/hr)					
		NO	NO ₂	CO	CO ₂	RSP	FORMALDEHYDE
Institute of Gas Technology 1986 (28,29) (continued)	Manufacturer H, 15,000 Btu/hr, infrared, LPG	1-7	40-92	427-1011	--	--	--
	Manufacturer I, 19,000 Btu/hr, infrared, natural gas	6-30	33-97	94-679	--	--	--
	Manufacturer J, 18,000 Btu/hr, infrared, natural gas	7-16	31-63	518-742	--	--	--
IIT Research Institute 1985 (30)	High fuel flow						
	Convective heater						
	Lean	203	111	105	--	--	--
	Rich	184	107	112	--	--	--
	Catalytic heater						
	Lean	1	2	69	--	--	--
	Rich	1	9	157	--	--	--
	Radiant heater						
	Lean	5	56	13	--	--	--
	Rich	6	63	14	--	--	--

* Dash (--) indicates data not reported.

The American Gas Association (AGA) tested 17 different gas-fired room heaters, five of which were unvented heaters. The average and range of the emissions reported by Thrasher and DeWerth are listed in Table 3-8 (23). Flue products were analyzed for CO, NO, NO₂, CH₄, ethylene (C₂H₄), and total aldehydes under well adjusted blue-flame and poorly adjusted yellow-flame conditions. The following observations and conclusions were made as a result of these tests:

- Burner adjustment affects emission levels. On the average, burners operating under yellow-flame conditions resulted in decreased NO levels, slightly higher NO₂ levels, and increased CO and CH₄ levels than blue-flame adjustment.
- There were no practical or statistically significant differences in the emission levels of vented and unvented type room heaters.
- It was possible to reduce NO_x emissions by as much as 55 percent by placing a screen in the burner flame; however, temperatures were increased, so different materials of construction were required.
- A heater in the field over a long period of time under minimum maintenance conditions may have significantly different emissions when compared to a new properly installed or an older properly maintained and adjusted appliance.
- As the fuel input rate is reduced below the normal operating rate, both the CO and NO₂ emissions increased while the NO and total NO_x levels are reduced. This is a result of lower flame temperatures.

Traynor, et al. conducted several extensive experimental studies on indoor air pollutants due to emissions from unvented gas-fired space heaters (24,25,26). In one study, emissions were measured from eight heaters under laboratory conditions and from four of these heaters under controlled field conditions (24,25). The heaters, with fuel input ratings ranging from 12,000 Btu/hr to 40,000 Btu/hr, were purchased from three U.S. manufacturers and had a blue-flame when well-tuned. The eight heaters were well-tuned and tested under laboratory conditions under full input and at approximately one-half the full input rating. However, the units are designed to operate at full rating. Manufacturers consider operating at partial input as misuse of the product. The range and average emissions are given in Table 3-8.

Four of the heaters were tested in an experimental research house under varying conditions. Pollutant concentrations were measured and the "average" emission rates determined by regression estimates of the pollutant source strength made between every two whole-house data points. The initial emission rate was determined within 5 to 15 minutes of ignition, and the final emission rate was the average of the last three semi-continuous emission rate points (between 1.5 and 7 hours). The initial, final, and average values of the emission rates are given in Table 3-8. As a result of the laboratory and field tests, the following observations were made:

- Although NO_x emission rates were fairly consistent among the eight well-tuned heaters tested in the laboratory, the emission rates for NO and NO_2 in individual heaters showed more variation. The CO emission rates of heaters tested in the laboratory were much more variable than those of other pollutants. CO is a product of incomplete combustion. Tuning tests illustrate the sensitivity of CO emissions to heater tuning.
- On the average, the emission rate for any measured pollutant was lower during partial input operation than during full input operation under laboratory conditions.
- Tuning affected CO, NO_2 , and formaldehyde concentrations the most. The minimum CO emission occurred near the same shutter setting as the maximum NO_x production, since the flame is hottest when there is the least amount of incomplete combustion.
- Very high CO and formaldehyde emissions were observed with the air shutter fully open due to incomplete combustion. Changes in emission rates due to air shutter adjustment in the laboratory were dependent on the type of heater, possibly due to differences in burner design.
- Pollutants mixed rapidly throughout the test house. It was suggested that this was due to the forced convection driven by the heater.
- In the test house, CO emission rates were not constant from heater to heater nor were they constant for an individual heater if the air/fuel ratio changed. CO emissions also changed with time. In the test house, as indicated by the data in Table 3-8, the NO, NO_2 , and NO_x emission rates changed over time, although the NO_x emission rates did not change as much as NO and NO_2 .
- In general, the particle and formaldehyde concentrations observed in the test house were low and emission rates were not reported.
- When the emission rates were not constant, the initial field emission rates from the test house usually agreed with the laboratory-derived rates.
- For CO, NO, and NO_2 , the actual use pattern of the heaters in the test house was critical in determining indoor pollutant levels since the emission rates changed over time.

- Concentrations of CO, CO₂, and NO₂ sometimes exceeded outdoor or occupational guidelines. Analysis showed that CO, NO, and NO₂ emission rates can vary with time and that, while short-term emission rates derived from laboratory tests were consistent with initial emission rates observed in the field, they did not always correspond to steady-state emission rates.
- Based on observed levels of CO₂ and NO₂ at or above existing standards or guidelines during most controlled field tests, unvented gas space heaters were found to pose a threat to the health of occupants living in a house where such appliances are used. Furthermore, based on factors such as the size of the heater, its state of tune, the volume and air exchange rate of the house, and the occupants' heater usage pattern and exposure to CO, CO₂, and formaldehyde, it was found that concentration limits set by environmental health or government agencies for these pollutants may also be exceeded and could pose a health hazard.

Analysis of the data taken during the first LBL investigation indicated that short-term laboratory-derived emission factors are not necessarily representative of long-term heater usage. As a result, the second investigation was designed to address this observation and to quantify emission factors of newer gas space heaters (26). Nine new heaters were selected for testing and all were equipped with an Oxygen Depletion Sensor (ODS). Among the nine, five were natural gas-fired heaters--four equipped with infrared tile burners and one with a blue-flame burner with ceramic radiating tile inserts. Four were propane gas-fired heaters--one equipped with an infrared tile burner and three equipped with blue-flame burners and ceramic radiating tile inserts.

Two emission rates are calculated from the data, one representative of the first or initial burn period (short period of heater operation) and a second or final burn period, representative of longer-period operation (for more than 90 minutes). Eighteen tests were run as duplicate tests for each heater to determine the initial and final emission rates. The average final emission rates, by heater design and type of fuel, show that:

- The NO₂ emission rate is dependent on burner design, but not type of fuel. Infrared tile burners produce significantly less NO₂ than blue-flame burners.
- CO and NO emission rates are dependent on both fuel type and burner design. Propane-fired blue-flame heaters produce less CO and more NO than the natural gas burners. Infrared heaters produce very little NO, regardless of fuel type.

Emission rates determined by the original and modified procedures for similar heaters were found to be generally comparable.

Fifteen other tests were performed to delineate the effect of fuel input rate, gas line pressure, primary aeration, and elevation above sea level on emission rates. The results of these tests are summarized as follows:

- In one infrared natural gas-fired heater, equipped with three tile burners, fuel input was reduced by sequentially eliminating fuel supply to each tile burner, resulting in three inputs of 14,900, 10,300, and 6,020 Btu/hr. Virtually no effect of fuel input on emission rate was found, except that the CO emission tended to increase as fuel input was reduced.
- The effect of gas-line pressure on emissions was measured with one infrared natural gas-fired heater and one propane-fired blue-flame heater. Virtually no effect was found.
- The effect of primary aeration or shutter adjustment was determined for two propane blue-flame heaters. Only minor variations were found in emission rates resulting from changes in shutter position.
- Operation of a propane blue-flame heater, at an elevation of 5,900 feet above sea level, resulted in increased CO, but reduced NO and NO₂ emission rates compared to operation at sea level.

Cote, et al. conducted a laboratory study to determine the emission rates of CO, NO, and NO₂ from unvented gas-fired space heaters (27). They operated an unvented gas-fired space heater under low flame, steady-state conditions with a heat input of 11,100 Btu/hr and then under high flame conditions with a heat input of 24,500 Btu/hr. The results of these tests indicate that emission rates were higher for all three pollutants while operating the heater at higher flame conditions.

In a more recent study on the measurement of emission rates from gas-fired space heaters, the Institute of Gas Technology (IGT), for the Gas Research Institute (GRI), conducted tests on ten unvented space heaters to compare the three test methods (e.g., probe, hood, and chamber) for measurement of emissions and to relate emissions to operating conditions (28,29). The results of the tests are as follows:

- For heaters equipped with blue-flame burners, average NO₂ emission levels are essentially the same irrespective of burner input rate and type, fuel type, method of measurement, and existence or absence of suspended radiating tiles.
- For natural gas-fired infrared heaters, NO₂ emission levels averaged from one-quarter to one-half of that from blue-flame heaters, but these levels appear to depend on heater (burner type and fuel input rate) design and method of measurement.

- The propane-fueled heaters exhibited the highest NO emission rates, consistent with expectations due to the very high adiabatic flame temperatures characteristic of propane gas flames. Natural gas-fueled blue-flame burners exhibited about one-half NO emissions while natural gas infrared burners produced virtually none.
- The natural gas-fired infrared heaters exhibited the highest average CO emission levels followed by the natural gas-fired blue-flame heaters and propane-fired blue-flame heaters. For each heater category, both burner (input rate and type) design and test method (chamber versus probe or hood) appear to have modest to large effects.
- Blue-flame propane heaters exhibited virtually no unburned hydrocarbon emissions, while natural gas blue-flame heaters and the infrared tile heaters generated some hydrocarbon emissions.
- Eight of the heaters were also previously tested by LBL using the chamber method. The overall comparison between LBL and IGT data showed no statistical differences in emissions of CO, NO, and NO₂. Some trends were observed when comparing specific heaters. The LBL CO and NO₂ emissions data tended to be higher than the IGT results, but in only a few cases were the differences statistically significant.
- In general, all three methods produce equivalent results for NO₂ emission factors.

The researchers expressed the opinion that an extra degree of caution is needed when the chamber method is used in place of the hood method to measure NO and CO emissions. It was also observed that the hood method has practical merits on which to base a test protocol because of the ease of use and the ability to specify a location over the space heater.

In another study for GRI, the IIT Research Institute tested three types of gas-fired unvented space heaters--convective, radiant, and catalytic. All of them were equipped with an oxygen depletion sensor (30). The rated gas input of the convective space heater was 10,000 Btu/hr. This heater was not equipped with gas input modulating controls. Both the radiant and catalytic space heaters were equipped with controls that allowed for three different heat output levels. The maximum rated gas input of the radiant heater was 15,000 Btu/hr and that of the catalytic heater was 12,000 Btu/hr.

Table 3-8 summarizes the emission rates of CO, NO, and NO₂ for the unvented space heaters. Typically, NO and NO₂ emission rates obtained were extremely low with the catalytic heaters and very low with the radiant heaters, compared to similar emissions from the convective heater. In contrast, relatively high non-combusted fuel emissions were found with the catalytic heater compared to the convective and radiant heaters. Emissions of CO from the radiant heater were very low compared to those from the convective or catalytic heaters.

In summary, studies have shown that emission rates from gas-fired space heaters vary for different brands and designs of heaters. The emissions also vary with the type of fuel input and the usage pattern of the heaters.

GAS-FIRED COOKING RANGES AND OVENS

The kitchen stove is one of few modern gas appliances that emits combustion products directly into the home. It is estimated that natural gas is used in approximately 64 percent of all U.S. homes, and studies show most of these homes do not vent the combustion-generated emissions to the outside (31). Pollutants produced by natural gas combustion in range top burners and ovens include: CO, CO₂, NO, NO₂, SO₂, RSP, and formaldehyde. Emission rates vary considerably and are dependent upon a number of factors, including:

- Usage pattern
- Appliance manufacturer and burner design
- Burner age
- Fuel consumption rate
- Combustion efficiency.

Table 3-9 summarizes the influence of these factors on the emissions of gas-fired cooking ranges and ovens. Gas stoves are typically used for relatively short time periods but are used throughout the year. Gas range top burners typically consume about 8,000 Btu/hr of energy each while fully on. Fuel consumption rates for gas-fired ovens operating at 350°F (180°C) for one hour are approximately 7,300 Btu/hr.

A number of experimental studies have been conducted to identify the pollutant emissions generated from gas burners and ovens. Some of these studies are summarized in Table 3-10. The remaining part of this section reviews the research efforts which have been performed with regard to unvented gas stove and oven emissions. Most of these studies have focused on observing the rates at which pollutants are emitted from gas stoves and ovens as well as the factors which influence such rates.

GRI has sponsored research projects at AGA Laboratory and at Thermo Electron on the reduction of pollutant emissions from gas range burners (33,34). The AGA Laboratory has developed a burner insert that lowers the average flame temperature and, therefore, reduces total NO_x emission by about 40 percent and NO₂ by about 30 percent; however, CO emissions increased but to levels still well below standards set by the American National Standards Institute. AGA is currently developing low NO_x emission burners for use in unvented gas space heaters (33).

Thermo Electron has developed a burner in which the combustion air is delivered by a blower and mixed with the gas prior to ignition. Combustion takes place just below the surface of a thin, perforated ceramic plate. The burner has reduced CO emissions as well as lowered NO_x and NO₂ emissions.

TABLE 3-9. INFLUENCE OF OPERATING FACTORS ON THE OBSERVED POLLUTANT EMISSION RATES FROM GAS STOVES AND OVENS

FACTOR	EFFECT
Burner Design	
Combustion air pre-mixing	<ul style="list-style-type: none"> • Reduced CO emissions and lower NO_x and NO₂ emissions for some burner designs (31,32)
Minimized flame surface	<ul style="list-style-type: none"> • Reduced NO_x and NO₂ emissions (34)
Grate material or design	<ul style="list-style-type: none"> • No effect on NO_x emissions (39)
Controlling secondary air supply	<ul style="list-style-type: none"> • Reduced NO_x emissions (39)
Lower flame temperature	<ul style="list-style-type: none"> • Decreased NO_x and NO₂ emissions and increased CO emission rates (40)
Burner Position (left, right, front, back)	<ul style="list-style-type: none"> • No systematic effects on NO₂ emission rates (44) • Higher CO and NO₂ emissions from front top burners than from rear top burners (39) • Probably an insignificant factor compared to others (42)
Fuel Input Rate ("high," "low," "medium," etc.)	<ul style="list-style-type: none"> • Increased NO₂ emissions and decreased NO with high fuel rates (39) • Decreased NO and NO_x emissions with high fuel rates; little or no increase in NO₂ emissions (37,38) • Significant effect on emission factors, especially on CO emissions (42)
Presence of Thermal Load (PAN) on Burner	<ul style="list-style-type: none"> • No effect on emissions (36) • Higher CO emissions with low flame and aluminum pan; NO₂ emissions lower (27) • Lower NO_x levels for larger pots and utensils (39) • Higher CO emissions at low flame with highest NO emissions at maximum flame; lowest NO emissions at low flame (43) • Higher CO emissions and lower NO and NO₂ emissions (33,38)

TABLE 3-9. INFLUENCE OF OPERATING FACTORS ON THE OBSERVED POLLUTANT EMISSION RATES FROM GAS STOVES AND OVENS (CONTINUED)

FACTOR	EFFECT
Gas Pilot Lights	
Oven or Stove	<ul style="list-style-type: none"> • Higher NO₂ levels for oven pilots (39)
Pilot Type	<ul style="list-style-type: none"> • Significant influence on NO₂ emissions (39)
Usage	
Concurrent Oven and Stove Operation	<ul style="list-style-type: none"> • No effect on emissions (39)
Number of Burners in Operation	<ul style="list-style-type: none"> • Increased pollutant levels (39)
Primary Aeration Rate (Tuning)	<ul style="list-style-type: none"> • Increased NO₂ and CO emission rates and reduced NO emissions with poor tuning (30,38) • Increased NO and NO₂ emissions with poor tuning (34) • Increased CO and NO₂ emissions with yellow flame condition in gas stoves; decreased NO and increased NO₂ emissions in ovens (39)
Operating Temperature of Gas-Fired Ovens	<ul style="list-style-type: none"> • Increased NO and NO_x emissions; no effect on NO₂ emissions (33)
Humidity of Ambient Air	<ul style="list-style-type: none"> • Lower NO and NO_x emissions at higher humidities (33)
Fuel Content of Gas Used	<ul style="list-style-type: none"> • No statistically significant effects on NO, NO₂, or NO_x emission rates (33)
Emission Rate Measurement Method	<ul style="list-style-type: none"> • Relatively small differences between observed emission rates of gas stoves for direct and mass-balance methods (30,33) • No significant differences (42)
Age of Appliance	<ul style="list-style-type: none"> • Increased NO₂ emission rates for older appliances (37)

TABLE 3-10. REPORTED SOURCE STRENGTHS OF GAS RANGES AND OVENS

STUDY	APPLIANCE TYPE AND OPERATING CONDITIONS	SOURCE STRENGTH (mg/hr)						
		NO	NO ₂	CO	CO ₂	SO ₂	RSP	FORMALDEHYDE
Bonneville Power Administration 1983 (2)	Gas-fired oven	30-90 ^a	130-270 ^b	1300-3000 ^a	383,000- 400,000 ^a	--	--	25 ^d
	Gas-fired burner	50-120 ^a	250-430 ^b	1800-2700 ^a	483,000- 550,000 ^a	--	10-30 ^a	15 ^d
Traynor, et al. 1978 (3)	Gas-fired oven operated at 350°F (180°C) for 1 hour. Fuel consumption rate is 7,970 Btu/hr Average	56 ^b	85 ^b	1,898	358,680	0.92	0.126 ^c 0.42 ^d	23
	Range	--	--	1,798-1,999	322,392- 389,424	0.67- 1.09	0.118- 0.126	20-28
	Gas-fired burner operated for 16 minutes. Fuel consumption rate is 8,730 Btu/hr per burner Average	89 ^b	136 ^b	1,840	416,944	1.47	4.6 ^c , 3.8 ^d	16
	Range	--	--	1,582-2,291	405,880- 437,420	1.29- 1.66	5.7 ^d	8-23
Coto, et al. 1974 (27)	Older gas stove with cast iron burners Pilot lights 596 Btu/hr	6.8	8.2	62.9	--	--	--	--
	1 burner, high flame 10,700 Btu/hr	250	140	1,031	--	--	--	--
	3 burners, high flame 26,900 Btu/hr	793	494	3,220	--	--	--	--
	Oven, steady-state 8,730 Btu/hr	201	161	1,166	--	--	--	--

TABLE 3-10. REPORTED SOURCE STRENGTHS OF GAS RANGES AND OVENS (CONTINUED)

STUDY	APPLIANCE TYPE AND OPERATING CONDITIONS	SOURCE STRENGTH (mg/hr)						
		NO	NO ₂	CO	CO ₂	SO ₂	RSP	FORMALDEHYDE
Cote, et al. (continued)	Newer gas stove with pressed steel burners							
	Pilot lights 400 Btu/hr	0.5	1.9	84.2	--	--	--	--
	1 burner, high flame 13,900 Btu/hr	455	277	1,795	--	--	--	--
	3 burners, high flame 40,500 Btu/hr	1,408	669	3,213	--	--	--	--
	Oven, steady-state 8,730 Btu/hr	171	111	3,564	--	--	--	--
Roschardreag, et al. 1985 ^h (30)	Range top burners Blue-flame 7,950-9,890 Btu/hr	130.6- 205.6	66.1- 116.5	179.6- 1,768.7	--	--	--	--
	Yellow-tipping flame 8,440-9,810 Btu/hr	104.7- 184.4	105.6- 189	625- 3,244	--	--	--	--
	Range-oven burners Bake 5,100, 5,400 Btu/hr	75.5, 83.1	59.7, 72.3	102.8, 390.3	--	--	--	--
	Broil 10,300-19,500 Btu/hr	254.4- 527.9	125.3- 204.5	202.5- 287.7	--	--	--	--
	Self-clean 12,100 Btu/hr	344.4	153.8	204.9	--	--	--	--
Himmel and Dewerth 1974 (39,40)	Gas-fired burner 9,000 Btu/hr	201- 220	74-114	155-353	--	--	--	--
	Gas-fired oven 11,000 to 24,000 Btu/hr	266- 581	67-146	195-426	--	--	--	--
	Top burner pilots 162 to 174 Btu/hr	2.0-2.5	0.7-1.4	5.5-12.7	--	--	--	--

TABLE 3-10. REPORTED SOURCE STRENGTHS OF GAS RANGES AND OVENS (CONTINUED)

STUDY	APPLIANCE TYPE AND OPERATING CONDITIONS	SOURCE STRENGTH (mg/hr)						
		NO	NO ₂	CO	CO ₂	SO ₂	RSP	FORMALDEHYDE
Himmel and Deuerth (continued)	Oven and broiler burner pilots 171 to 177 Btu/hr	0.005- 0.4	1.8-3.2	27-98	--	--	--	--
		165-176	87-104	195-1,769	--	--	--	--
Cole, et al. 1983 (41)	Gas range 1, non-standing gas pilot lights, fuel input rate for individual burners 8680-9060 Btu/hr Rich gas (1022 Btu/scf)	163-182	84-97	257-1,456	--	--	--	--
	Lean gas (983 Btu/scf)							
	Gas range 2, non-standing gas pilot lights, fuel input rate for individual burners 7950-8670 Btu/hr Rich gas (1022 Btu/scf)	131-151	75-105	236-813	--	--	--	--
	Lean gas (983 Btu/scf)	135-164	66-76	213-675	--	--	--	--
	Gas range 3, standing gas pilot lights, fuel input rate for individual burners including pilot burners 9130-9890 Btu/hr Rich gas (1022 Btu/scf)	163-206	105-117	180-563	--	--	--	--
	Lean gas (983 Btu/scf)	155-177	101-110	191-670	--	--	--	--
Goto and Tamura 1984 (43)	One burner, with pot operated at maximum setting, 8200 Btu/hr	147	130	753	--	--	--	--
	Two burners, with pots operated at low setting 2275 Btu/hr	19	36	382	--	--	--	--
	One burner, without pot operated at maximum setting, 8200 Btu/hr	173	121	450	--	--	--	--

TABLE 3-10. REPORTED SOURCE STRENGTHS OF GAS RANGES AND OVENS (CONTINUED)

STUDY	APPLIANCE TYPE AND OPERATING CONDITIONS	SOURCE STRENGTH (mg/hr)						
		NO	NO ₂	CO	CO ₂	SO ₂	RSP	FORMALDEHYDE
Borrazzo, et al. 1987 (46)	Range burner 8,532 Btu/hr	153	108	882	--	--	--	--
	Oven 390°F (200°C), 0-15 min 17,064 Btu/hr	360	396	2,700	--	--	--	--
	390°F (200°C), 15-60 min 8,532 Btu/hr	126	99	297	--	--	--	--
	500°F (260°C)	211	154	317	--	--	--	--
	9,100 Btu/hr				--	--	--	--

a Adapted from Gilman, J.R., et al., Pollutant Emissions and Source Strengths from Indoor Combustion Appliances and

Smoking, Lawrence Berkeley Laboratory, Berkeley, California, 1981.

b Calculated from NO and NO₂ data.

c Dash (--) indicates data not reported or otherwise not available.

d Adapted from National Research Council, Indoor Pollutants, National Academy Press, Washington, D.C., 1981.

e Assumes a volumetric NO₂-to-NO ratio of 1.0, actual measurements varied from 0.4 to 2.0.

f Particles (<0.5 microns) based on electrical mobility analysis and assuming a particle density of 2.0 g/cm³.

g Particles (<2.5 microns) based on gravimetric analysis of filters.

Coutant, et al. studied NO and NO₂ emissions from range-top burners and pilot flames (34). The study showed that the production of NO₂ in gas flames involves processes that occur early in the combustion process while NO formation occurs throughout the combustion process. As a result of these studies, it was determined that NO and NO₂ emissions could be reduced from the range-top burners and pilot flames by:

- Improving primary aeration using 50 percent or greater primary air.
- Using flame geometries designed to minimize flame surface (for example, flat-flame burners or other designs having effectively fewer distinct ports).

The emission rates of various pollutants generated from a gas-fired stove in an environmental chamber by Traynor, et al. are listed in Table 3-10 (3,10). Because ovens are thermostatically controlled, two emission rates were used to describe emissions over time: one for the initial heating cycle (from 0 to 11 minutes) and one for steady-state operation (from 11 to 60 minutes). The reported emission rates from the oven are time-weighted averages of these two rates. They concluded that the principal difference between the emission rates from the top burner and the oven is the high level of respirable particulates emitted from the top burners. Girman, et al. reported similar data on emissions from gas-fired stoves in other reports (14,35).

Cote, et al. monitored CO, NO, and NO₂ emissions from various burner configurations and operating modes for a new and old stove (27). These stoves produced low, but continuous emissions from the pilot light. Cote, et al. also measured emissions from top burners while water-filled pans of different materials were being heated. They noted minor effects on gas-flame emission, especially with a low flame. When an aluminum pan was used, CO concentrations were higher, and with all types of pans under low-flame conditions, NO₂ concentrations were slightly lower than without pans. However, Hollowell, et al. found no appreciable differences in gaseous emissions, regardless of the types of pans used (36).

In a recent study for AGA, IIT Research Institute studied three ranges, each operated at two levels of primary aeration: (1) properly adjusted primary air shutters (blue-flame) and (2) primary shutters completely closed (yellow-tipping flame) (37,38). Emission rates of CO, NO, and NO₂ are shown in Table 3-10. Although not shown in the table, no major differences were found between the average emission rates estimated by the mass balance and direct methods. Some of the conclusions of the study are:

- The emission rates from range-top burners do not vary substantially with time.
- The effect of fuel type on the magnitude of emission rates was minor. Pipe gas was used in a small number of experiments. The in-chamber concentrations with the pipe gas were similar to corresponding values obtained with gas specially treated for this study.

- Statistical analyses of the data generated for this study indicate that the type of indoor combustion source and the primary aeration level have a significant impact on the CO, NO, and NO₂ emission rates. Although statistically significant, the effect of the air infiltration rate is not as pronounced, possibly because of variations in chamber relative humidity and temperature, which affect the indoor contaminant concentration. Statistically significant differences may be of little or no importance from the practical point of view since the variations across all independent parameters are small.
- Emission rates from range-top burners estimated without thermal load were higher for NO and NO₂ and lower for CO than with thermal load.
- One of the three ranges tested had pilot lights; the NO₂ and CO emission rates of the pilot lights are similar in magnitude (per Btu) to the corresponding emission rates from the range-top burners. This, however, does not lead to similar indoor NO₂ and CO concentrations because the rated fuel input rates for all three pilot lights are approximately 11 percent of the range-top burner fuel input rate.
- The NO and NO_x emission rates from a range oven are affected by the maximum temperature of the operational mode (from bake to self-cleaning). The NO and NO_x emission rates for the bake mode are lower than the corresponding rates from the broil and self-clean modes (highest temperature). The emission rates of NO₂ are not affected substantially by oven temperature; the CO emission rates do not follow a clear pattern.
- The highest possible fuel input rate (firing rate) was used for the experiments with range-top burners. Decreasing the fuel input rate of a range-top burner has an impact on the emission rates of NO and NO₂. The NO and NO_x emission rates decrease as the fuel input rate decreases, whereas the NO₂ emission rates remain constant or decrease slightly. This is an important finding because range-top burners are frequently operated at lower rates than the maximum fuel input rate.

Himmel and DeWerth tested 18 different natural gas-fired ranges for AGA (39,40). The emissions from pilot burners, top burners, ovens and broilers, infrared burners, burners with thermostatic control, ovens and broilers with catalytic cleaning panels, and pyrolytic cleaning ovens were analyzed for CO, NO, NO₂, CH₄, ethylene, and SO₂. The effects of cooking utensil materials used with top burners on NO_x formation were also observed. A summary of the ranges of CO,

NO, and NO₂ emissions reported by Himmel and DeWerth for normal operating conditions is listed in Table 3-10. The following conclusions were made as a result of the tests conducted:

- Burner fuel input rate and the number of burners in operation have a significant effect on the NO_x emission level.
- NO_x emissions for top burners could be reduced by controlling the inflow of secondary air to the flame, by placing something such as a screen in the flame to reduce flame temperature, and by operating a burner at 100 percent plus primary aeration.
- Top burners operating in a yellow-flame condition resulted in increased CO and NO₂ emissions and decreased NO emissions due to a lower flame temperature.
- Decreasing the rate of a burner by adjusting the dial setting resulted in increased NO₂ and decreased NO emissions.
- Reducing the fuel input rate of top burners resulted in statistically significant reductions in NO, NO₂, and NO_x emissions.
- An increased emission rate of NO and NO₂ was observed from thermostatically-controlled range-top burners.
- Emissions of particulate matter, formaldehyde, polynuclear aromatic hydrocarbons, and volatile organic compounds were measured and found to be low compared to CO and NO_x.
- Experiments confirmed that the presence of indoor surfaces (fabric, carpet, etc.) reduced indoor NO₂ concentrations.
- The emission rates of formaldehyde and TSP were lower than the corresponding rates found in the literature.
- Changing oven and broiler burners from blue- to yellow-flame conditions decreased NO and increased NO₂ emissions.
- The overall NO_x emission is lower for the oven than the top burners. There is not much difference in NO_x emissions between oven burner pilot types.

Cole, et al. studied the emission rates from three gas-fired domestic ranges under controlled laboratory conditions (41). Emission factors were determined for individual range-top burners fired with two types of fuel mixtures: rich [1,022 Btu/standard cubic feet (scf)] and lean (983 Btu/scf). A summary of the resulting range of source strengths from individual burners is

provided in Table 3-10. Cole, et al. also tested ovens operated in several different modes, simulating bake, broil, or self-cleaning operations. A parametric analysis based on the t-test was used to compare pairs of average emission rates from different burners or different fuels. The major conclusions drawn from this analysis include the following:

- For a specific range and with only minor exceptions, NO, NO₂ and NO_x emission rates are independent of burner position (left, right, front, or rear).
- The NO, NO₂, and NO_x emission rates were not substantially affected by the fuel content of the gas (rich or lean). However, some systematic trends were observed, but were found not to be statistically significant. The NO emission rates for two of the ranges tended to be somewhat higher when the rich gas was used, while the opposite was true for another. For all three ranges, NO₂ emission rates increased slightly when the rich gas was used.
- For one range, CO emission rates were found to be higher from the rear burners (0.383 and 0.272 lb/million Btu) than the front burners (0.096 and 0.138 lb/million Btu). Although not as pronounced, a second range exhibited similar trends. For another range, the highest CO was found for the right front burner, with the other burners exhibiting lower values.
- The CO emission rate was not affected by fuel content of the gas (rich or lean).

Borrazzo, et al. collected and analyzed published emission rate data to investigate the importance of three binary factors: burner position, sampling method, and type of combustion (42). In general, they concluded that the first two factors (burner position and sampling method) were relatively unimportant in explaining the observed variance for CO, NO, and NO₂ emission rates. However, roughly 50 percent of the observed variance in log ER (base 10 logarithm of the emission rate) for CO, 30 percent of that for NO₂, and a fraction of that for NO and NO_x can be explained by the influence of the type of combustion. Test results showed that stove differences were significant for NO, NO₂, and CO. Burner position had a smaller, but statistically significant effect in explaining the variance in CO and NO₂ emissions, while the sampling method had a small, but statistically significant, effect on NO_x emissions.

Other conclusions of this effort were:

- Of the factors studied, stove differences and combustion adjustment were the most important in explaining the observed variances in emission rates.
- Limited data suggest that CO emission rates could vary significantly with gas flow rate, while those for NO and NO₂ exhibited less variability.

Moschandreas and Relwani investigated the influence of the age of the gas range on NO₂ emission rates (37). The results, shown in Table 3-10, illustrate a trend of increased NO₂ emission rates with increasing appliance age, although appliance design may have an impact on the observed variation of NO₂ emission rates.

Goto and Tamura reported on tests sponsored by The National Research Council of Canada in an energy-efficient test house with a gas cooking stove (43). Using the enclosed kitchen as a test chamber, emission rates for CO, NO, and NO₂ were determined (see Table 3-10). The CO emission rates were higher when burners were operated with pots than without, and at lower rather than maximum settings. The NO emission rate was highest with one burner at maximum setting with a pot and lowest with two burners and water-filled pots at low setting. The emission rates for NO₂ were about the same for the three conditions.

Borrazzo, et al. estimated CO, NO, and NO₂ emission rates from a gas stove and oven using a mass balance model and measured concentrations in a modern townhouse (44). The corresponding source strengths, calculated from the given firing rates for these appliances, are given in Table 3-10. Burner position (left, right, front, or back) was found to have no systematic effect on calculated NO₂ emission rates.

In summary, the above studies indicate that the design of range-top burners influences pollutant emission rates. Emission rates are generally independent of burner position for NO, NO₂, and NO_x; however, CO emission rates are influenced by the burner position. Variations in the fuel content of the gas did not substantially affect CO, NO, NO₂, or NO_x emissions. Finally, a higher level of respirable particle emissions results from the use of top burners rather than ovens.

WOODSTOVES, FURNACES, AND FIREPLACES

Woodstoves, furnaces, and fireplaces are vented to the outdoor atmosphere; however, they can contribute to indoor levels of many different pollutants including CO, CO₂, NO, NO₂, SO₂, RSP, BaP, and formaldehyde. Improper installation, cracks or leaks in stovepipes, negative air pressure indoors, downdrafts, refueling, and accidents can create circumstances that cause combustion products to be emitted to the indoor atmosphere. The rate of emissions will also depend on the following factors:

- Usage pattern
- Manufacturer and type of appliance
- Type of wood burned.

A summary of the factors that have been investigated relative to their effects on emission rates from woodburning appliances is presented in Table 3-11.

Wood combustion occurs primarily during the cold months of the year. Periods of start-up and refueling increase the possibility of pollutant emissions to the indoor atmosphere. Woodstoves, woodburning furnaces, and fireplaces are residential wood combustion systems that consist of a device capable of holding

TABLE 3-11. INFLUENCE OF OPERATING FACTORS ON THE OBSERVED POLLUTANT EMISSION RATES FROM WOODBURNING APPLIANCES

FACTOR	EFFECT
Manufacturer and/or Type of Appliance	
Airtight versus non-airtight	<ul style="list-style-type: none"> • Only minor amounts of pollutants emitted by airtight stoves while a non-airtight model was a major source of TSP and CO (4,51,52) • Significant increases in particulates and PAHs from open fireplaces (52) • Higher CO, TSP, RSP, and NO emissions for non airtight models (45)

wood and an attached chimney to carry flue gases to the outside air. There are a wide variety of manufacturers and types of woodburning devices. The type and amount of wood burned influences the pollutant emissions and can, therefore, influence indoor pollutant concentrations.

While a number of experimental studies have reported concentrations of pollutants resulting from woodburning, there is little information available on emission rates to the indoors from such devices. These units are designed to vent to the outdoor atmosphere. However, they may emit relatively small quantities of pollutants over a long period of time into the room (i.e., emissions resulting from leaks). On the other hand, relatively high emission rates may occur for a short period of time (i.e., emissions during refueling).

A number of studies which have measured indoor pollutant concentrations during woodburning activities are described in Section 5, Indoor Concentrations. Some studies have resulted in observations concerning emissions. They are summarized in Table 3-12 and discussed briefly below.

Knight, et al. conducted a three-year study to determine the impacts of indoor air quality associated with operating both airtight (conventional and catalytic) and non-airtight wood heaters in a weatherized home. The Tennessee Valley Authority (TVA), the Bonneville Power Administration, and the Consumer Product Safety Commission all provided funding for this study (45,46).

A single, relatively tight [air exchange rate (ACH) = 0.4] test home was used. Indoor and outdoor air samples were monitored continuously using electronic analyzers with CO, NO, NO₂, NO_x, ozone, oxygen, hydrocarbon, and SO₂ concentrations recorded. The wood heaters tested during this study included three conventional airtight (AT) units, six catalytic airtight units, and three non-airtight wood heaters. Emission rates, measured over a broad range of burn rates, indicate that the non-airtight wood heaters generate significantly higher levels of CO, total suspended particulates (TSP), and RSP. They also operate with higher NO and NO₂ emissions.

TABLE 3-12. REPORTED SOURCE STRENGTHS OF WOOD HEATERS

STUDY	APPLIANCE TYPE	SOURCE STRENGTH (mg/hr)							FORMALDEHYDE
		NO	NO ₂	CO	CO ₂	SO ₂	TSP	Bap ^b	
TVA/BPA (1983) (45)	Airtight, Catalytic, Radiant	0.6,0.8	0.3,0.7	70,375	--	--	4.2,42.9	--	--
	Airtight, Conventional, Circulatory	1.3	0.7	162	--	--	5.0	--	--
	Airtight, Conventional, Radiant	0.8	0.7	95	--	--	5.7	--	--
CPSC (1984) (45)	Non-Airtight, Box-Type, Radiant	2.0-4.0	2.1-3.6	210,416	--	--	11.9,12.7	--	--
	Franklin-Type, Freestanding	9.4	3.1	530	--	--	20.6	--	--
TVA/BPA (1985) (45)	Catalytic, Radiant, Airtight	0.4-2.6	-2.8-0.9	55-182	--	--	4.1-7.5	--	--
	Conventional, Radiant, Airtight	3.2	2.4	69	--	--	4.3	--	--
	Wood Heater 1 Average	--	--	162	--	--	--	--	--
Knight and Mumfryes (1986) (46)	Wood Heater 2 Average	--	--	70	--	--	--	--	--
	Wood Heater 3 Average	--	--	95	--	--	--	--	--
	Wood Heater 4 Average	--	--	375	--	--	--	--	--
	Woodstove Clean	1.2	1.3	86	--	--	2.6	0.014	--
Treynor, et al. (1987) (51)	Dirty	3.9	7.0	560	--	--	100	0.25	--
	Airtight	--	--	11.9-166	--	--	2.5-8.7	0.02-0.76	--
	Non-Airtight	--	--	261-2,136	--	--	16-230	2.2	--

^a Dashes (--) indicate data not reported.^b = µg/hr.

Imhoff reviewed data on emissions in homes with woodstoves collected by Moschandreas, et al. and Neulicht and Core (47,48,49). In general, TSP, RSP, BaP, and CO concentrations were higher during woodburning periods. Woodstove emission rates calculated from the information reviewed are listed in Table 3-12. Imhoff observed that some stoves (clean) had little effect on indoor air quality because of low emissions. Other (dirty) stoves emitted substantial amounts of pollutants indoors. Whether a stove is "clean" or "dirty" is the result of one or a combination of such factors as: stove design, installation, maintenance, and operation.

In another study, Moschandreas, et al. monitored pollutant concentrations in residences with woodstoves and fireplaces (50). The following observations were made concerning pollutant emission rates:

- Woodburning appears to be a potential major source of particle emissions within the residential environment.
- The impact of woodstove operation on indoor RSP concentrations is less than fireplaces due to the closed combustion chamber design of the stoves.
- Woodburning appears to have an impact on CO levels, probably due to back drafts when a stove is opened for refueling.

Traynor, et al. studied emissions from two woodburning stoves and two woodburning furnaces under uncontrolled actual living conditions (9). House A had a woodburning furnace in the basement and a woodburning stove in the living room. House B had a woodburning stove in the living room and House C had a woodburning furnace in the basement. Measurements of CO, NO, NO₂, and SO₂ were made and are discussed further below. In another study, Traynor, et al. tested four models of woodburning stoves in a house (51). Measurements were made of CO, NO, NO₂, formaldehyde, TSP, suspended particles (<0.6 microns), and hydrocarbons. As a result of these tests, the following observations, related to pollutant emissions, were made:

- Elevated levels of all pollutants monitored were observed in all houses during the period of operation. In general, the pollutant levels were below occupational and outdoor air quality standards (9).
- In House B, the NO emitted by the stove appeared to leak slowly but continuously rather than intermittently. However, in House C, the NO₂ levels measured during the operation of the woodburning furnace did appear to be episodic. This may be due to emissions during warm-up before a sufficient draft was created in the flue (9).
- Emissions vary considerably in terms of the mix of pollutants emitted and their total contribution to pollutant levels (9).

- All woodburning stoves tested emitted at least trace amounts of CO and suspended particles on real-time peaks that corresponded to starting, stoking, and/or reloading times (51).
- In general, the airtight stoves emitted only minor amounts of pollution indoors. However, one non-airtight stove was a major source of TSP and CO, causing levels to reach or exceed standards (51).

Sexton, et al. conducted an indoor/outdoor monitoring study at 24 homes, 18 with woodburning appliances (2 with kerosene heaters) and 6 without (4). They concluded that RSP concentrations are frequently elevated indoors, even in the absence of tobacco smoke. No statistical difference was observed between 24-hour average indoor respirable particle levels in homes that did not burn wood and those that did. Findings suggested that airtight woodstoves can be installed, operated, and maintained in such a way that the direct release of particles to the environment is negligible.

Quraishi and Todd, in an overview of the effects of domestic woodburning on indoor air quality, concluded that woodburning, especially in open fires (such as in open fireplaces), can cause significant decreases in indoor air quality by increasing the concentration of respirable particulates and polycyclic aromatic hydrocarbons (52). However, it was found that the effects of operating non-leaking heaters are negligible.

In summary, elevated levels of CO, NO, NO₂, SO₂, and particles have been measured during woodburning; however, emissions vary considerably in terms of the mix of pollutants and have been found to be emitted continuously or intermittently.

TOBACCO SMOKE

Tobacco smoke is a highly complex mixture of gases, vapors, and particulates caused by the combustion of tobacco. In addition to the pollutants commonly produced by the combustion of other substances (e.g., CO, CO₂, NO, and NO₂), the burning of tobacco produces relatively small amounts of more than 1200 other pollutants (53).

An important concept in the research of tobacco smoke is the distinction between mainstream (that which is inhaled directly by the smoker) and sidestream (that which is released to the ambient air) smoke. Sidestream tobacco smoke has been reported to be more alkaline, contains much greater quantities of water, and has greater CO₂/CO ratios than mainstream smoke. Particle size distributions are also said to be smaller in sidestream smoke (54). In some cases, emission rates for sidestream smoke are estimated from mainstream smoke emission rates.

Over the years, many researchers have measured pollutant emissions from various tobacco products, mainly cigarettes. Measured emissions from a number of these studies are presented in Table 3-13. These studies are briefly described below.

TABLE 3-13. REPORTED EMISSION RATES FOR CIGARETTES

STUDY	TOTAL EMISSION RATE (mg/CIGARETTE)							FORMALDEHYDE
	NO	NO ₂	CO	CO ₂	RSP	BaP		
National Research Council, 1981 ^a (5)	b	0.065 ^{a,b}	105 ^a	143 ^a	-- ^c	1.7x10 ^{-4a}	1 ^a	
Girman, et al. 1981 ^a (14)	--	--	78.0 ^a	--	10.8 ^a	--	--	
Moschandreas, D.J., et al. 1985 ^a (30)	2.78 ^a	0.73 ^a	88.43 ^a	555.5 ^a	17.7 ^d	--	--	
Guerin, et al. 1989 (54) ^a	b	0.4 ^{a,b}	25 ^a -49.3 ^a	160 ^a -320 ^a	19.5 ^a	5x10 ⁻⁸ to 9x10 ⁻⁸	0.035- 0.050	
Woods, 1983 ^a (55)	--	0.079 ^a	51.6 ^a	443 ^a	--	--	--	
Health and Welfare Canada ^a 1984 (56)	--	--	21 ^a	--	--	--	--	
Rickert, et al. 1984 (57)	--	--	53 ^a 65 ^a	--	--	--	--	
Boeleij and Brundkreef ^a 1982 (58)	--	--	100 ^a	--	30-40 ^a	2.0x10 ^{-8a}	--	
Repace, 1984 ^a (60)	--	--	--	--	32.5 ^a	--	--	

^a Sidestream emissions.^b NO_x emission rate, reported as NO₂^c Dash (--) indicates data not reported^d Total particulate emission rate^e Mainstream plus sidestream emissions.

Girman, et al. conducted experiments in an environmental chamber under controlled ventilation (14). Pollutant concentrations were measured and emission rates were then calculated for sidestream cigarette smoke. The reported emissions of pollutants are given in Table 3-13.

Moschandreas, et al. used research cigarettes produced by the Tobacco and Health Research Institute at the University of Kentucky for the cigarette smoke study (30). The composition of these cigarettes is comparable to a high sales volume cigarette (e.g., Merit). For this study, standard puff conditions were maintained. The smoke produced by puffing through the cigarette, and by smoldering between puffs, was accumulated within the environmental chamber. Only one type of cigarette and standard puff condition were evaluated in this study. All experiments were performed at an air infiltration rate of 1.0 air changes/hr and with five cigarettes burning simultaneously. It took about 9 minutes to burn the five cigarettes using the standard puff conditions established by the Federal Trade Commission. Once these five cigarettes burned, another set of five cigarettes was lighted automatically. In a single experiment, 20 cigarettes were burned, with only five cigarettes burning simultaneously at any given time.

Emission rates for CO, CO₂, NO, NO₂, and particulates were calculated for all the experiments. Table 3-13 shows the average emission rates for CO, CO₂, NO, NO₂, and particulates. A striking difference in the NO₂ emission rates from cigarettes is evident between the Moschandreas values and those reported by other studies. No obvious cause of this discrepancy is available; however, it is speculated that the difference may be attributable to the milligrams per cigarette smoked (Moschandreas 800 mg/cigarette versus conventional 600 mg/cigarette), the type of cigarettes smoked (standardized versus commercial), or the method of calculations.

Guerin compiled data from a number of sources to estimate the average emissions per cigarette for a number of particles and gases (see Table 3-14) (54). It was observed that the indoor concentrations depend on the number of smokers, how the tobacco is smoked (cigarette, pipe, or cigar), the room volume, the volume of fresh air makeup, the efficiency of an air-cleaning apparatus, and the effectiveness of air mixing in the room. The adsorbing characteristics of building and furnishing materials can also affect the concentration. It was also concluded that tobacco smoke may be the most important source of exposure of non-smoking populations to BaP, nicotine, and other compounds in non-industrialized areas.

Woods reported generation rates of indoor pollutants resulting from tobacco smoke (55). The pollutant emissions reported are listed in Table 3-15.

Health and Welfare Canada investigated CO yields of a number of brands of cigarettes (56). These experiments were conducted at a research facility, LABSTAT. The organization conducted tests with one single-port and two 20-port smoking machines which smoke at predetermined rates, leave fixed butt lengths, and allow researchers to measure the levels and concentrations of substances inhaled. The reported data are given in Table 3-16 and summarized in Table 3-13. The tar, nicotine, and CO yields are from the burning end of cigarettes (sidestream smoke). All brands tested delivered more tar, nicotine, and CO in the sidestream than the mainstream smoke. When mainstream and sidestream levels

TABLE 3-14. COMPOSITION OF MAINSTREAM AND SIDESTREAM CIGARETTE SMOKE

CONSTITUENT	QUANTITY PER CIGARETTE		RATIO SS/MS
	SIDESTREAM	MAINSTREAM	
Particulates	-	15-40 mg	1.3-1.9
Particulates	15.8-36.0 mg	2.5-19.4 mg	0.9-14.4
Particulates	19.7-23.4 mg	11.6-46.4 mg	0.4-1.8
Nicotine	-	1.0-2.5 mg	2.6-3.3
Nicotine	2.7-6.1 mg	0.3-1.2 mg	2.4-22.4
Nicotine	5.9-7.0 mg	0.6-2.1 mg	3.0-12.5
Carbon Monoxide	-	10-23 mg	2.5-4.7
Carbon Monoxide	40.5-67.3 mg	2.6-20.5 mg	2.6-20.6
Carbon Monoxide	49.3-63.0 mg	2.4-20.4 mg	2.7-23.4
Carbon Dioxide	-	20-40 mg	8-11
Nitrogen Oxides	-	100-600 µg	4-10
Ammonia	-	50-130 µg	40-170
Hydrogen Cyanide	-	400-500 µg	0.1-0.25
Formaldehyde	-	70-100 µg	0.5-50
Benzene	-	12-48 µg	5-10
Toluene	-	100-200 µg	5.6-8.3
Pyridine	-	16-40 µg	6.5-20
Aniline	-	0.36 µg	30
o-Toluidine	-	0.16 µg	19
Phenol	-	60-140 µg	1.6-3.0
Benzo(a)pyrene	-	20-40 ng	2.5-3.5
2-Naphthylamine	-	2 ng	30
4-Aminobiphenyl	-	5 ng	31
N-Nitrosodimethamine	-	10-40 ng	20-100
-diethylene	-	ND-20 ng	[40
-pyrrolidine	-	[10-30 ng	6-30
-nornicotine	-	0.2-3 µg	0.5-3
-diethanolamine	-	20-70 ng	1.2
NNK ^a	-	0.1-1 µg	1-4
Cadmium	-	0.1 µg	7.2
Nickel	-	20-80 ng	13-30
Polonium 210	-	0.04-0.1 pCi	1-4

^a 4-(N-methyl-N-nitrosamino)-1-(3-pyridyl)-1-butanene.

Source: Guerin, M.R., "Formation and General Characteristics of Environmental Tobacco Smoke," Combustion Processes and the Quality of the Indoor Environment: Transactions of an International Specialty Conference, Air and Waste Management Association, Pittsburgh, Pennsylvania, 1989.

TABLE 3-15. GENERATED CONTAMINANTS FROM CIGARETTE SMOKING

CONTAMINANT	EMISSION RATE (mg/CIGARETTE)
NO _x	0.079
CO	51.6
CO ₂	443.0
Ammonia	5.2
Aldehydes	0.114
Hydrogen Cyanide	0.065
Acrolein	0.011
Nicotine	4.2
Phenols	0.636
Pyridines	1.3
Total Suspended Particles	31.9

Source: Woods, J., et al., "Calculation Methods to Assess Indoor Air Quality," presented at the ASHRAE Annual Meeting, June 1983.

TABLE 3-16. CARBON MONOXIDE YIELDS OF 50 BRANDS OF CIGARETTES AVAILABLE IN CANADA^a

AVERAGE TAR YIELD mg/CIGARETTE ^b	AVERAGE NICOTINE YIELD mg/CIGARETTE ^b	BRAND NAME	AVERAGE CO YIELD mg/CIGARETTE
0.4	0.04	Viscount No. 1 Ultra Mild Regular FT ^c	0.5
0.7	0.07	Viscount No. 1 Ultra Mild KSFT ^d	1
1	0.1	Macdonald Select Ultra Mild KSFT	1
1	0.1	Medallion Ultra Mild KSFT	2
1	0.1	Craven "A" Ultra Light KSFT	1
3	0.3	Viscount Extra Mild KSFT	4
4	0.4	Craven "A" Special Mild KSFT	5
4	0.4	Matinée Extra Mild KSFT	4
4	0.4	Viscount Extra Mild 100's FT	5
5	0.5	Vantage Light KSFT	6
8	0.5	Matinée Regular FT	12
8	0.6	Craven "A" Regular FT	11
9	0.8	Player's Extra Light Regular FT	9
9	0.9	Silk Cut King Size FT	11
9.5	0.6	Gitanes Caporal Regular FT	16
9.5	0.8	Loblaw's "No Name" Light Virginia FT	6
10	0.8	Belvedere Extra Mild Regular FT	13
10	0.8	Export "A" Light Regular FT	12
10	0.8	Vantage KSFT	14
11	0.6	Gitanes KSFT	16
11	0.7	Gauloises Disque Bleu Caporal Regular FT	13
11	0.7	Gauloises Caporal Regular FT	15
11	0.8	Craven Menthol KSFT	11
11	0.8	Matinée KSFT	13
11	0.9	du Maurier Special Mild KSFT	12
12	0.9	Rothmans Special Mild KSFT	15
12	1.0	Craven "A" KSFT	12
12.6	0.9	La Québécoise Regular FT	14
13	1.0	du Maurier Regular FT	17

TABLE 3-16. CARBON MONOXIDE YIELDS OF 50 BRANDS OF CIGARETTES AVAILABLE IN CANADA^a (CONTINUED)

AVERAGE TAR YIELD mg/CIGARETTE ^b	AVERAGE NICOTINE YIELD mg/CIGARETTE ^b	BRAND NAME	AVERAGE CO YIELD mg/CIGARETTE
14	1.0	Player's Light Regular FT	16
14	1.0	Export "A" Medium Regular FT	16
14	1.1	Loblaw's "No Name" Virginia KSFT	16
14	1.2	La Québécoise KSFT	17
15	1.1	Belvedere Regular FT	18
15	1.1	Mark Ten Regular FT	21
15	1.3	Tremblay KSFT	17
16	1.1	Black Cat No 7 KSFT	18
16	1.1	Rothmans KSFT	17
16	1.1	Mark Ten KSFT	19
16	1.1	Cameo KSFT	20
16	1.2	du Maurier KSFT	18
16	1.2	Peter Jackson KSFT	17
17	1.0	Player's Regular Plain	13
17	1.1	Export "A" Regular FT	18
17	1.2	Player's Regular FT	18
17.5	0.9	Gitanes Regular Plain	15
17.5	1.0	Gauloises Regular Plain	14
18	1.0	Sportsman Regular Plain	15
18	1.1	Export "A" Regular Plain	15
18	1.2	Mark Ten Plain KS	15

^a Average tar, nicotine, and CO yields are determined by machine smoking 100 cigarettes under the following standard conditions: puff volume--35 ml; puff duration--2 sec; puff interval--58 sec; and butt length--30 mm

^b Printed on package

^c FT: Filter tip

^d KS: King size

Source: "Research that Goes Up in Smoke," Research and Development Bulletin, Canada, No. 132, March 1984.

were totaled, there were no statistically significant differences between ventilated and non-ventilated cigarettes. The data indicated that "light" and "mild" cigarettes, which are generally ventilated, yield just as much tar, nicotine, and CO as regular filter cigarettes when mainstream plus sidestream emissions are considered.

In another study conducted at LABSTAT, Rickert, et al. investigated emissions of tar, nicotine, and CO in the sidestream smoke from 15 brands of Canadian cigarettes (57). The average CO emissions in the sidestream and mainstream are included in Table 3-13. Sidestream yields of tar, nicotine, and CO were much higher than mainstream yields for all brands tested. The highest yields of sidestream were obtained from the brands with the lowest mainstream yields. The average total yields for the 15 brands were 36 mg of tar, 5 mg of nicotine, and 65 mg of CO.

Boleij and Brunekreef reported typical emissions from cigarettes (see Table 3-13) based on their review of a number of sources (58). However, they suggest that these values can change as new types of cigarettes are being developed. Repace reported that one out of three adults is a cigarette smoker and typically smokes 32 cigarettes in a day, resulting in an estimated emission rate of 65 mg/hr of particulates into the environment (59). Repace and Lowrey reported on tests related to tobacco smoke, ventilation, and indoor air quality (60). They investigated the relative smolder-stream emissions of high-, medium-, and low-tar cigarettes. They found that the sidestream emissions were not significantly different for low- and average-tar cigarettes (60,61).

OTHER INDOOR COMBUSTION SOURCES

Several other combustion sources can affect indoor air quality to varying degrees. These emission sources, however, are not as widely used or as common as domestic gas heating and gas stove appliances.

Gas Water Heaters and Gas Clothes Dryers

Indoor emissions from unvented gas-fired water heaters and clothes dryers have not received much attention to date, and as a result, few quantitative data are available on this topic. Generally, both gas water heaters and gas clothes dryers are designed to be vented to the outdoor atmosphere. The emissions collection efficiency of the water heater flue collar is presumed to be high; however, there are occasions when emissions do leak past the collar, and as a result, enter the interior living space.

The National Research Council, through personal communication with G.W. Traynor at LBL, noted that, for two homes with vented gas water heaters, indoor concentrations of NO₂ were measured at levels greater than ambient outdoor concentrations (2). Passive (diffusion) monitors were employed to measure average indoor concentrations during a one-week period and a continuous analyzer was used later to monitor and measure NO₂ concentrations within the homes. These data are reported to have demonstrated that for both homes, NO₂ entered the living space from the flue collar located atop the water heater, despite the fact that the flue collar was designed to collect combustion products and vent them outside the home.

Moschandreas, et al. tested one gas-fired dryer, equipped to vent indoors as per manufacturer's procedure for GRI (30). The fuel input rate for the dryer was 20,000 Btu/hr. The emission rates of CO, NO, and NO₂, obtained from the direct and mass balance methods are shown in Table 3-17. The emission rates of CO, NO, and NO₂, derived by the two methods were different. There are two possible explanations for the difference: (1) the difference in the in-chamber relative humidity and (2) the method of calculation of the emission rate. These differences could be due to the dryer burner on-off cycle, which is initiated after about 15 minutes of continuous operation. Because of this on-off cycle in the mass balance method, the emission rates were calculated for the first 15 minutes of the burn period. For the direct method, the emission rates were computed as integrated averages of the multiple measurements.

A similar on-off cycle for the range oven has made a direct comparison of the two methods inappropriate, since the emission rates do not reflect the same operational conditions.

TABLE 3-17. SOURCE STRENGTHS FOR GAS DRYER FROM MASS BALANCE AND DIRECT METHODS

COMPOUND	SOURCE STRENGTH, mg/hr	
	MASS BALANCE METHOD ^a	DIRECT METHOD ^b
NO	159	189
NO ₂	168	146
CO	1,413	554

^a Three tests were performed. Average fuel input rate = 19,457 Btu/hr. Emission rates calculated for 15 minutes of burn period.

^b Four tests were performed. Average sample CO₂ = 0.52%, and fuel input rate = 13,400 Btu/hr.

Source: Moschandreas, D.J., et al., Characterization of Emission Rates from Indoor Combustion Sources, Final Report (March 1982 - March 1985), GRI 85/0075, IITRI C08765-Final, March 1985.

Automobile

Driving a car into or out of a basement garage or an attached garage can strongly affect residential indoor air quality, depending on the design and tightness of the home. The National Research Council reported that in a number

of documented cases, occupants have unknowingly left a car motor operating while parked in a basement garage from which the resulting CO emissions drifted into the attached home or apartment and caused sickness or death to residential occupants (5). Notably, the most critical situation would occur in a basement garage during cold weather. The "stack effect" of a heated home causes cold air to flow into a home from the garage and distribute the garage pollutants throughout the house. An analogous situation occurs in an office building or apartment house with a basement garage that has either stairwells or elevators shafts that could potentially distribute pollutants throughout the building.

Little information is available on the impact of automotive exhaust emissions on indoor air quality. Yocom, et al. sampled one house with an attached garage and concluded that the design of the split-level house caused automobile emissions from the garage to have a greater impact on CO concentration than a gas-fired range (62).

Charcoal Cooking

Charcoal cooking is usually an outdoor activity; however, on occasion it is done in an indoor fireplace. Depending on how such cooking is carried out and how strongly the fireplace flue draws, the resulting combustion emissions can enter the indoor environment (5). There appears to be no data available concerning the direct impact of charcoal cooking on indoor air quality, but a study by Brookman and Birenzvice on exposure to air pollutants emanating from domestic combustion sources provides some idea of how great these exposures might be (63). Hourly CO ranged from 8 to 38 ppm at a sampler near the charcoal cooker. At the high levels (38 ppm), over a number of hours, adverse health effects may be observed.

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Section 4

FACTORS AFFECTING POLLUTANT CONCENTRATIONS

INTRODUCTION

The concentration of combustion-generated pollutants in the indoor atmosphere is dependent on various factors affecting the introduction, dispersion, and removal of the pollutants. Pollutants are introduced from indoor sources or from the outdoor air which then are distributed over time throughout a residence. Pollutants are removed from the indoor atmosphere by air exchange and chemical and/or physical reactions. In other words, the quality of indoor air is the result of a number of concurrently operating factors which combine and/or interact to produce desirable or undesirable concentrations of one or more indoor air pollutants. At the most basic level, an indoor air pollution problem can be described as a situation in which the rate of pollutant input into a structure or room has exceeded, to an unacceptable degree, its rate of output and reaction.

The basic factors influencing the indoor concentration of pollutants are:

- Source emission strength and rate
- Outdoor pollutant concentration/ambient air
- Air exchange rate
- House volume and rate of mixing
- Pollutant reactivity rate.

A number of general conclusions regarding the influence of each of these factors can be made in accordance with reported observations (see Table 4-1). Increases in the number of pollutant sources or the magnitude of source strengths result in increased indoor pollutant levels. The impact of increased air exchange on the level of air pollutants in a structure depends on the quality of the ambient air; however, in most (but not all) cases, the quality of outdoor air is better than that found indoors, and increased effective air exchange rates are, therefore, beneficial to indoor air quality. In general, decreased air exchange rates can be expected to concentrate pollutants generated indoors. Homes with larger volumes tend to have lower overall concentrations of indoor-generated pollutants, probably due to dilution effects. The reaction of pollutants indoors is a significant factor affecting their removal, but only for certain pollutants. These and other factors are discussed in this section with regard to their affect on indoor pollutant concentrations.

Pollutant concentrations in a residence vary with location and time of measurement. Peaks occur initially near the pollutant source until dispersion and removal mechanisms produce more uniform concentrations throughout the house. For intermittent emissions, these peaks can exist for a relatively short period of time. Once the emissions stop, the concentration drops off due to dilution and/or pollutant reactivity. Under these circumstances, the average pollutant concentration can be much lower than the peak concentration. Pollutants which

TABLE 4-1. INFLUENCE OF FACTORS ON THE OBSERVED POLLUTANT CONCENTRATIONS IN INDOOR ENVIRONMENTS

FACTOR	CORRELATION
Presence of Specific Pollutant Sources	
Unvented Kerosene Heaters	<ul style="list-style-type: none"> • High indoor NO_2 levels; some heaters account for high particulate levels (1).
Woodburning Stoves and Fireplaces	<ul style="list-style-type: none"> • Some types account for high particulate levels (1).
Tobacco Products	<ul style="list-style-type: none"> • High particulate levels (1).
Gas Ranges	<ul style="list-style-type: none"> • Unvented types correlate to high peak NO_2 levels (1). • Gas-piloted types correlate to higher indoor air pollutant concentrations than electronic-piloted types (2). • Higher NO_2 levels for homes with "gas cookers" (3).
Unvented Gas Space Heaters	<ul style="list-style-type: none"> • Probable cause for high NO_2 levels (2).
Gas-Fired Ovens	<ul style="list-style-type: none"> • Older ovens sometimes account for higher kitchen NO_2 levels (4).
Automobile	<ul style="list-style-type: none"> • Sometimes high CO levels (1).
Gas and Oil-Fired Furnaces	<ul style="list-style-type: none"> • High predicted NO_2 levels in some houses (5).
Gas-Fired Floor Furnaces	<ul style="list-style-type: none"> • High NO_2 levels (2).
Wall Furnaces	<ul style="list-style-type: none"> • High NO_2 levels (2).
Usage Patterns	<ul style="list-style-type: none"> • Use of spot ventilation correlates to large reductions in indoor CO, CO_2, and NO_x (6,7). • High NO_2 levels associated with use of gas ovens as space heaters (2,4,8). • Frequency of oven use correlates to high NO_2 concentrations (4).
Outdoor Pollutant Concentration/Ambient Air	<ul style="list-style-type: none"> • Largest single source of indoor NO_2 in certain parts of Southern California (4).
Air Exchange Rate	<ul style="list-style-type: none"> • Higher NO_2 levels in areas with high outdoor NO_2 levels (4). • Little effect for small reductions (less than 15%) in air exchange rate; changes of 50 percent found to have substantial impact on pollutant levels (9). • Relatively little effect on peak pollutant concentrations (5,6,10). • Concentrations of reactive pollutants may not be directly related to air exchange rate (10,11,12,13). • Low air exchange rates may cause vented indoor combustion appliances to back-draft (14,15,16). • Air exchange rate of 0.3 to 0.5 air changes/hr sufficient for the average home to meet OSHA and NAAQS standards (17). • Strong correlation between air exchange rate and indoor pollutant concentrations not always present (18,19).

TABLE 4-1. INFLUENCE OF FACTORS ON THE OBSERVED POLLUTANT CONCENTRATIONS IN INDOOR ENVIRONMENTS (CONTINUED)

FACTOR	CORRELATION
House Volume and Rate of Mixing	<ul style="list-style-type: none"> • Negative correlation to NO_2 levels (2,4). • Higher NO_2 levels in kitchens than in bedrooms (2). • Higher NO_2 in older homes than in newer homes (2).
Reactivity	<ul style="list-style-type: none"> • Types of materials and relative humidity relate to degree of NO_2 removal (20,21). • Reduced NO_2 and NO concentrations with activated carbon (22). • No measurable removal in a sealed chamber (23).

are emitted at a relatively constant rate will result in more constant indoor pollutant concentrations, although variations in other factors may cause fluctuations. With relatively constant source strength and other factors remaining relatively constant, the average concentration over time may not differ significantly from the peak concentration.

Empirical data indicate that for intermittent pollutant sources, the source strength, house volume, and rate of mixing are the primary factors affecting peak pollutant concentrations. However, over time, the source strength and duration, the outdoor pollutant concentration, and the air exchange rate are the primary factors affecting long-term average pollutant concentrations. The influence of the pollutant reactivity rate, in general, is uncertain with wide ranges in reactivity rates reported in individual building studies.

In recent years, research and experimental studies have been conducted to gain an understanding of the elements which influence indoor pollutant concentrations. A discussion of the effects of emission source, pollutant distribution, and removal mechanisms on pollutant concentrations and the results of some of these studies follows in this section. The next section (Section 5, Indoor Concentrations) presents the results of studies reporting pollutant concentrations indoors and provides a description of the methods and instrumentation techniques available for measuring concentrations.

SOURCE EMISSION STRENGTH AND RATE

The sources which contribute to a pollutant concentration in a residence may have emission rates which are relatively constant or which vary with time. The time dependent generation rates may be caused by operating source equipment or appliances intermittently, or at varying capacities, or by periodically moving a source, such as a kerosene heater.

- Continuous Emissions--Sources may generate pollutants continuously or for a long enough time that pollutant concentrations reach a relatively steady level. For example, NO_x concentrations were monitored by Hawthorne, et al. in a house with a kerosene space heater used as a supplemental source of heat. Once the heater was turned on, concentrations rose until they reached a fairly steady level about an hour later (see Figure 4-1) (24).
- Intermittent Emissions--Sources may emit pollutants for relatively short periods of time, causing peaks in pollutant concentrations. For example, NO_x concentrations of two operating gas burners were monitored by Hawthorne, et al. The NO_x concentration rose steadily until shortly after the burners were turned off, and then dropped rapidly so that original concentrations were observed within an hour (see Figure 4-2) (24).

A combination of sources will often contribute to pollutant concentration simultaneously. Variations in source emissions will influence the pollutant concentration throughout a residence. If no combustion-generated pollutant sources are located within a residence, then indoor combustion-generated

Figure 4-1. NO_x Levels Associated with the Operation of a Kerosene Space Heater

Source: Hawthorne, A.R., et al., "Results of a Forty-Home Indoor Air Pollutant Monitoring Study," presented at the 76th Annual Meeting of the Air Pollution Control Association, 1983.

Figure 4-2. NO_x Levels in a Room Adjacent to a Gas Stove. Two Burners Were Operated Between Times A and C and February 2, 1983.

Source: Hawthorne, A.R., et al., "Results of a Forty-Home Indoor Air Pollutant Monitoring Study," presented at the 76th Annual Meeting of the Air Pollution Control Association, 1983.

pollutant concentrations will generally approximate outdoor concentrations. However, in the case of pollutants which are reactive in the indoor environment or when controls such as filters or precipitators are used to remove some of the pollutants from the make-up air, lower indoor concentrations may result. Emissions sources were discussed in detail earlier in Section 3, "Emissions from Combustion Sources."

AIR EXCHANGE RATE

Residential buildings protect people from the outdoor elements and separate the indoor and outdoor air. There may be relatively little exchange between the two air masses. Different factors influence their interaction, resulting in different concentrations of pollutants indoors and outdoors. The replacement of indoor air with outdoor air removes contaminants from within the building but can also introduce outdoor pollutants.

The rate of air exchange is expressed as air changes per hour (ACH). It is the number of times in an hour that a volume of outside air equal to the internal house volume enters the house. The following basic mechanisms cause air exchange between the indoor and outdoor environments.

- Infiltration--Air leakage inward through cracks and interstices, and through ceilings, floors, and walls of a space or building. Air movement occurs due to pressure differences.
- Natural Ventilation--The movement of air into and out of a space through intentionally provided openings, such as windows and doors, or through non-powered ventilators or by infiltration.
- Mechanical Ventilation--Forced movement of air between the indoors and outdoors produced by fans.

The rate at which air is exchanged by these mechanisms depends on a variety of factors:

- Building Construction Methods and Materials--The shape of a building determines the amount of surface area exposed to the external environment and, therefore, greatly influences infiltration (25). Figure 4-3 illustrates common infiltration sites in a house. Table 4-2 is based on measurements in houses in the southern and western regions of the United States. Building shape and orientation to the wind influence the distribution of wind pressures, which cause infiltration (see Figure 4-4) (26). Also, building height becomes important due to buoyancy of warm air. Tightness of construction will affect the location and degree of infiltration. The location of doors, windows, and other intentional openings not only affects the location and extent of infiltration, but also determines where natural and forced ventilation may occur. The installation of fans will influence the degree of air exchange by mechanical ventilation. Operating fireplaces in homes will also tend to increase air exchange rate (27).

Figure 4-3. Infiltration Sites

Source: Lawrence Berkeley Laboratory, Manual on Indoor Air Quality, Report No. EM-3469, for Electric Power Research Institute (Research Project 2034-3), Palo Alto, California, February 1984.

House-Wind Orientation			
End Units	Air Infiltration Average	Interior Units and Tree Sheltering	Air Infiltration Average
1	1.486	1	1.240
2	2.358	2	1.259
3	2.256	3	0.141
4	1.948	4	0.863
5	1.098	5	0.738
6	0.786	6	0.860
7	0.058	7	0.498

Figure 4-4. Effects of Orientation and Wind Barriers on Air Infiltration in Townhouse Units. Arrow Indicates Wind Direction. X Indicates Unit Tested. Dashed Lines Indicate Wind Breaks. Infiltration Average in ACH

Source: Mattingly, G.E. and E.F. Peters, "Wind and Trees: Air Filtration Effects on Energy in Housing," Journal of Industrial Aerodynamics, Vol. 2, pp. 1-19, 1977.

TABLE 4-2. COMPONENT AIR LEAKAGE VALUES, %

COMPONENT	RANGE	AVERAGE
Walls/Floor	18-50	35
Ceiling	3-30	18
Heating system	3-28	15
Windows/Doors	6-22	15
Fireplace	0-30	12
Vents	2-12	<u>5</u>
TOTAL		100

Source: Lawrence Berkeley Laboratory, Manual on Indoor Air Quality, Report No. EM-3469, for Electric Power Research Institute (Research Project 2034-3), Palo Alto, California, February 1984.

- Climate and Surrounding Terrain--The pressures established by temperature differences and wind cause infiltration. Wind and temperature can vary greatly over short distances. They are strongly influenced by the terrain and obstacles surrounding a building. Hills, valleys, surrounding buildings, and vegetation influence wind direction, speed, and turbulence and may also block solar radiation (27). The air exchange rate due to infiltration will generally increase with increasing wind speed and temperature difference as indicated in Figure 4-5 (28).
- Occupant Lifestyle--Maintenance performed on a house which creates or closes leaks will influence infiltration. Also, the location and operation of fans affect ventilation. In effect, people control the degree to which natural and mechanical ventilation are used to increase the air exchange rate. In addition, the number of times and length of time doors and windows are opened and closed will affect the rate.

The air exchange rate is greatly influenced by the forces of the external environment acting on the building. The dominant factor in determining a building's infiltration rate is the total area of effective leakage. Following the leakage area in importance are the terrain and shielding near the building, the mean climatic conditions, and the building height (29).

Figure 4-5. Air Change vs. Wind Speed and Temperature Difference. Infiltration Increases with Wind Speed and Indoor-Outdoor Temperature Difference

Source: Stranden, E. and L. Berteig, "Radon in Dwellings and Influencing Factors," Health Physics, Vol. 39, pp. 275-284, 1980.

Typical Air Exchange Rates

Typically, the air exchange rates for U.S. residences without house tightening measures, as estimated in a report for the Bonneville Power Administration, are within the following ranges (11):

- Single-family detached house--0.5 to 1.5 ACH
- Single-family attached house--0.35 to 1.0 ACH
- Mobile homes--0.3 to 1.5 ACH
- Apartments--0.3 to 0.9 ACH.

The National Research Council is in agreement that typically the air-infiltration rate for American residences is assumed to be 0.5 to 1.5 ACH (29). This estimate is supported by energy and air-quality studies, which determined experimentally the range of ventilation rates for typical residences to be between 0.7 and 1.1 ACH. Based on limited data, recently built or retrofitted residences had lower rates, between 0.5 and 0.8 ACH (29).

Infiltration rates from two surveys of U.S. houses are illustrated in Figure 4-6. The values shown for the 312 newer houses are calculated averages of the infiltration rates over the heating season, November through March. The average of the seasonal infiltration values is 0.63 ACH and the median value is 0.50 ACH. For the 266 low-income houses, single measurements were taken. The average infiltration value is 0.9 ACH. The higher average value is partly because these houses are typically older and not as tightly constructed (25).

The air exchange rates in the same house may vary enormously from day to day and even hour to hour, depending on the speed and direction of the wind and the temperature difference between indoors and outdoors. Figure 4-7 shows the variability of the air exchange rate in a Chicago house.

In recent years, there has been a trend towards tighter construction for energy-efficient houses. Builders today can construct houses that have air exchange rates as low as 0.1 ACH. However, these houses often use mechanical ventilation to reduce moisture and pollutant build-up.

For new construction, special techniques used for reducing air infiltration include installation of a continuous plastic sheet inside the walls on the warm side (in winter) of the insulation to reduce air leakage through walls and around windows and door frames. Polymeric-foam can be used to seal the cracks and holes that are made during construction (25).

For existing buildings, retrofit measures include caulking and weather-stripping doors and windows, installing foam gaskets behind outlet boxes, taping and sealing leaky ducts, adding plugs to fireplaces, and other techniques involving sealing.

Berk and co-workers measured air exchange rates and the influence on indoor air quality for three energy-efficient homes (12). The air exchange rates averaged about 0.2 ACH and ranged between 0.1 and 0.4 ACH. Figure 4-8 illustrates the variation in the air exchange rate observed over a 24-hour period in one of the energy efficient homes.

Ventilation standards have been developed by a number of organizations, including the American Society of Heating, Refrigerating, and Air-Conditioning Engineers (ASHRAE) and the American National Standards Institute (ANSI). Ventilation rates (see Section 7, Indoor Air Quality Standards) are typically specified in cubic feet per minute (cfm) per person rather than ACH due to the sensitivities of spacial dimensions and occupancy. These standards can be converted to equivalent ACH depending on the size of the room and number of people occupying it. For example, 5 cfm/person for a 1000 cubic feet (ft^3) room with one person would be equivalent to a requirement of 0.3 ACH for that room.

Air Exchange Effects on Indoor Pollutant Concentrations

In general, lower air exchange rates result in higher concentrations of contaminants from indoor sources. However, reactive contaminants such as NO_2 , formaldehyde, radon daughters, and suspended particles are removed by physical or chemical reactions in addition to air exchange. Therefore, the concentration of these pollutants may not be directly related to the air exchange rate (10,11,12,13). The air exchange rate plays an increasingly greater role with time and has relatively little effect on initial peaks in the indoor pollutant concentrations (10). Reduced air exchange can contribute to high pollutant

INFILTRATION RATES FROM A SURVEY OF 312
HOUSES CONSTRUCTED IN THE UNITED STATES
AND CANADA

INFILTRATION RATES FROM A SURVEY OF 266
LOW-INCOME HOUSES IN THE UNITED STATES

Figure 4-6. Infiltration Rates in United States Houses

Source: Lawrence Berkeley Laboratory, Manual on Indoor Air Quality, Report No. EM-3469, for Electric Power Research Institute (Research Project 2034-3), Palo Alto, California, February 1984.

Figure 4-7. Variations in Air Exchange Rate in a Chicago House

Source: Lawrence Berkeley Laboratory, Manual on Indoor Air Quality, Report No. EM-3469, for Electric Power Research Institute (Research Project 2034-3), Palo Alto, California, February 1984.

Figure 4-8. Time Dependence of Infiltration Rate

Source: Berk, J.V., et al., "Indoor Air Quality Measurements in Energy-Efficient Houses," presented at the Air Pollution Control Association 72nd Annual Meeting, Ohio, June 1979.

concentrations due to draft reversal in furnaces without safety shutoffs or fireplace chimneys, when the demand for air by fireplaces and/or furnaces and exhaust fans exceeds the air supplied by leakage area and supply ducts (14,15,16).

In a study conducted by Goto and Tamura, measurements of gas stove emissions in an energy efficient test house indicated that increasing the house air infiltration rate from 0.1 to 0.9 ACH resulted in a reduction of only about 20 percent for peak CO and NO₂ concentrations in the kitchen (30). However, operating the range hood at 22 liters/second (sec) reduced the peak concentration by about half that obtained by natural air infiltration, and to a negligible level at 94 liter/sec. They also found that air contaminant levels between cooking episodes were much greater in houses with low air infiltration rates than those with higher rates.

Sexton, et al. investigated the effects of residential wood combustion on indoor air quality by conducting a field study and using a linear regression model to evaluate the predictive capability of potentially significant variables (31). Air exchange rate was determined to be one of the significant variables of indoor RSP concentrations. However, even when data on outdoor particle values, heating fuel use, home characteristics, and air exchange rate are included in a model of RSP, only about 20 percent of the inter-home variance in indoor RSP levels can be explained.

Hollowell and co-workers conducted laboratory studies on CO and NO₂ concentrations resulting from gas oven emissions at various air exchange rates (10). Figures 4-9A and 4-9B illustrate the levels of CO and NO₂ observed in the experimental room at various ventilation rates. These tests were conducted with the oven of the gas stove operated at 350°F (175°C) for 1 hour. Offermann and co-workers found that with air exchange rates of 0.2 to 0.5 ACH in nine different houses, some with gas appliances, indoor concentrations of radon, formaldehyde, and NO₂ were low enough to suggest that the source strengths of these contaminants were relatively low in these houses (13). The average indoor concentration of NO₂ did not exceed 23 parts per billion (ppb). Cain and Leaderer found that the total suspended particulate mass concentrations achieved during smoking (8 cigarettes/hr) at a ventilation rate of 2.2 ACH resulted in higher levels than outdoor standards (32). Monat and Chin developed a model for calculating the minimum acceptable infiltration rate that conserves energy while maintaining adequate indoor air quality based on National Ambient Air Quality Standards and OSHA Standards (17). Although recommended acceptable infiltration rates are dependent on the house layout and on occupant behavior, they determined that an infiltration rate of about 0.3 to 0.5 ACH is sufficient for the average home to maintain air quality at these standards.

Traynor and co-workers investigated the effects of ventilation on pollutant concentrations resulting from the operation of combustion appliances (3,7). The effects of infiltration and two types of mechanical ventilation on CO, CO₂, NO, and NO₂ concentrations from a gas-fired stove were studied in an unoccupied experimental research house with a volume of 260 cubic meters (m³). A range hood was used to evaluate spot ventilation and a ventilation system incorporating a cross-flow, air-to-air heat exchanger was used for whole-house ventilation

Figure 4-9A. Carbon Monoxide Concentrations in a 27 m³ Experimental Room at Various Air Exchange Rates

Source: Hollowell, C.D., J.V. Berk, and G.W. Traynor, "Impact of Reduced Ventilation on Indoor Air Quality," ASHRAE Journal, July 1979.

Figure 4-9B. Nitrogen Dioxide Concentrations in a 27 m³ Experimental Room at Various Air Exchange Rates

Source: Hollowell, C.D., J.V. Berk, and G.W. Traynor, "Impact of Reduced Ventilation on Indoor Air Quality," ASHRAE Journal, July 1979.

tests. For one study, 15 ft³ of natural gas were burned for each experiment reported while the type and amount of ventilation were varied. In a second study, 15 ft³ of natural gas were burned with the oven set at 350°F (175°C) and two top burners set on high flame. They demonstrated that the initial peak in indoor pollutant levels is relatively independent of the air exchange rate which, over time, played an increasingly greater role. Spot ventilation increased the air exchange rate to about twice that obtained with whole house ventilation, and it reduced NO_x levels in the kitchen to about one-sixth of those observed in the whole house ventilation experiment. Experiments also showed that the range hood reduced the average source strengths of CO, CO₂, and NO_x by 60 to 87 percent. They determined that both the type and amount of ventilation have important effects on the indoor pollutant levels. As shown in Figure 4-10, although whole house ventilation lowered peak one-hour average pollutant levels in all rooms, spot ventilation was more effective than whole-house ventilation in removing the gaseous contaminants.

Numerous studies have indicated that other factors in addition to air infiltration influence pollutant concentrations and, therefore, a strong correlation cannot always be found between air exchange rate and pollutant concentration. For example, NO₂ concentrations measured in 15 new low infiltration homes, some with gas appliances, ranged from 2.6 to 28 ppb at air exchange rates of about 0.15 to 0.5 ACH (see Figure 4-11) (18).

In studies sponsored by the Bonneville Power Administration, Grimsrud, et al. monitored air exchange rates and indoor air pollution in a collection of homes located in the Pacific Northwest (33). The air exchange ranges of newly constructed residences and older residences before and after weatherization were measured to determine if a correlation existed between the quality of indoor air and the air exchange rate. It was observed that:

- Standard house infiltration reduction techniques reduced building leakage areas by 15 percent, while a reduction of 50 percent was reported for more methodical techniques.
- On average, standard weatherization and house tightening appeared to have "minimal" impact on concentrations of indoor pollutants.
- For houses tightened by the most comprehensive techniques, changes in pollutant concentrations proved to be substantial.

Despite these findings, the authors stressed the importance of pollutant sources and pollutant emission rates in the creation of high pollutant concentrations over the effects of reducing the infiltration rates through house tightening, and described the effect of reducing infiltration rates as more of an exacerbation of existing problems than as the creation of new ones.

Traynor, et al. described a study performed on two connected single-story residences, one control and one test, located in Albany, Oregon (34). House volumes were measured, and pollutants were introduced through the use of thermostatically-controlled unvented gas space heaters. Measurements of induced pollutant levels in both houses were made; a subsequent tightening of the test

Figure 4-10. Nitrogen Dioxide Concentration vs. Ventilation in an Experimental Research House. Fifteen ft³ of Natural Gas Were Burned in a Gas Stove for Each Experiment

Source: Traynor, G.W., et al., The Effects of Ventilation on Residential Air Pollution Due to Emissions from a Gas-Fired Stove, Report No. LBL-12563, Lawrence Berkeley Laboratory, Berkeley, California, 1981.

Figure 4-11. The Average Indoor Concentrations of Nitrogen Dioxide vs. Average Infiltration Rates in 15 New, Low-Infiltration Homes

*Long term average for one year.

Source: Lawrence Berkeley Laboratory, Energy Efficient Buildings Program Chapter, FY 1982 Annual Report, Berkeley, California, March 1983.

house from 0.43 to 0.071 ACH was also conducted. The results showed that while both houses initially exhibited similar concentrations of pollutants, the subsequent tightening of the test house dramatically increased the level of indoor pollutants in that house. An interesting observation was that increasing the insulation effectiveness of the test house effectively reduced the indoor pollutant levels in that house, presumably by reducing the necessary on-time of the space heater. It was concluded that while reducing air exchange rates in homes by tightening or weatherizing them may tend to increase indoor pollutant levels in homes with indoor combustion pollutant sources, improving the insulating ability of the home can offset such effects.

Infiltration of Pollutants

At varying rates, the air in virtually all houses is exchanged with the ambient (outdoor) air. In general, this action is beneficial to the quality of indoor air since outdoor air is usually characterized by much lower pollutant concentrations. Under certain conditions, however, the air surrounding a home may contain higher concentrations of specific pollutants than indoor air, and thus outdoor air may be a significant contributor to indoor air pollution. Relatively high outdoor air pollutant concentrations may be due to a number of factors, including:

- Location--The location of a house relative to a major outdoor pollution source can affect outdoor air quality. Residences located near major streets or highways may be affected by the pollution generated from vehicles, smokestacks, flues, vents, and cooling towers. In general, urban and industrialized areas have higher concentrations of pollutants than rural areas. In at least one case, the outdoor pollutant levels in an entire region (Southern California) have been noted to be significantly correlated with indoor concentrations (2).
- Time--There may be significant fluctuations in the concentration of outdoor pollutants over time. Day/night or seasonal patterns may occur due to variability in meteorological factors (such as thermal inversions) and variations in the usage rates of local sources such as fireplaces and woodstoves during the winter.

Although in a number of cases outdoor air may be a significant contributor to indoor air pollutant concentrations, this effect may be alleviated by the shielding effect of a house, particularly for more reactive pollutants or pollutants which may be physically filtered. The use of the indoor/outdoor (I/O) concentration ratio for a given pollutant is useful in assessing the importance of the shielding effect (when no significant indoor sources of that pollutant are present) of a home with regard to specific pollutants. Assuming that no indoor sources are present, pollutants which are observed to have I/O ratios less than unity could be inferred to be shielded by the home, while pollutants with I/O ratios of unity could be considered to be not significantly shielded by the home.

Yocom prepared a critical review of indoor-outdoor air quality studies with an emphasis on indoor pollutants resulting from either outdoor sources or both indoor and outdoor sources (35). A number of the reviewed studies are included in the following tables (Tables 4-3 through 4-7). Yocom concluded that evidence indicated that indoor and outdoor air are substantially different.

The I/O ratios for NO_2 are usually less than 1.0 when there are no indoor sources. With indoor sources present, such as unvented gas stoves, I/O ratios for NO_2 in excess of 5.0 can occur in a kitchen, and can exceed 1.0 in other sections of the house (35). Table 4-3 summarizes the results of some studies conducted on NO and NO_2 I/O ratios.

The Residential Indoor Air Quality Characterization Study sponsored by the Southern California Gas Company yielded a number of interesting results. In a study performed by Baker, et al. and Colome, et al., measured indoor NO_2 levels in approximately 600 homes in the Los Angeles Basin were analyzed to identify the factors that influence indoor NO_2 level variations (2,4,8). They concluded that although a number of factors were shown to influence NO_2 levels in the homes surveyed, the largest single contributing variable to indoor NO_2 in Southern California was outdoor NO_2 .

Baker observed that on average, homes in the Los Angeles basin area with lower air exchange rates (weatherized or energy-efficient) were more likely to be associated with lower NO_2 than homes with higher air exchange rates (2). One-week average indoor NO_2 concentrations were found to be proportional to outdoor NO_2 levels. In addition, indoor NO_2 appeared to vary seasonally with the highest indoor NO_2 concentrations reported in the winter for most homes and appliance types. It should be noted that the high winter concentrations may be due to increased use of gas-fired heating appliances in a home which has less ventilation. Other factors influencing the high NO_2 concentrations were the relatively high ambient NO_2 levels and increased window use (and in general, higher activity levels in the home) (4).

In a study of indoor and outdoor NO_2 levels in England and Wales, Atkins and Law found that houses with no indoor sources of NO_2 afford some protection from outdoor NO_2 (3). The degree of protection was found to be independent of outdoor NO_2 concentrations and varied according to an established pattern, being greater in winter than in summer.

Long-term average I/O ratios for CO tend to be close to unity when there are no indoor sources of CO. Short-term ratios may depart from this condition as a result of non-equilibrium conditions which exist prior to distribution of the CO (35). The results of some experimental studies are given in Table 4-4.

The I/O ratio for CO_2 is influenced by human occupancy density and the use of unvented combustion devices. Available data show that outdoor CO_2 concentrations vary widely, depending on sources, activities, air exchange rate, and season of the year (see Table 4-5).

There is considerable variability in the data about the I/O relationships for SO_2 . However, indoor levels of SO_2 have been found to be consistently below outdoor ambient levels (see Table 4-6). Yocom suggests that during the winter

TABLE 4-3. SOME I/O STUDIES OF NITRIC OXIDE AND NITROGEN DIOXIDE

STUDY AUTHORS	SUMMARY OF RESULTS	CONDITIONS
Atkins and Law 1987 (3)	Homes without gas cookers had I/O ratios of from 0.38 to 0.68.	Data collected consisted of continuous measurements conducted at three homes and single measurements conducted in 51 homes over two-week sampling periods. Homes with and without gas cookers were investigated.
Baker, et al. 1987 (8)	The I/O ratio of NO ₂ ranged from 1.2 to 5.5.	50 homes recording high levels of indoor NO ₂ were selected for monitoring of I/O ratios.
Yocom 1982 (35)	Without indoor sources, outdoor NO ₂ concentration patterns over-predict indoor exposures by a factor of about 2.	Conclusions are based on a critical review of indoor-outdoor air quality studies.
Thompson, et al. 1973 (36)	The I/O ratio for NO ₂ for non-air conditioned buildings ranged between 0.49 and 1.0. One house with air-conditioning had an I/O ratio of 0.37.	A wide range of buildings were monitored to investigate various types of air-conditioning and cleaning system effects on I/O ratios.
Moschandreas, et al. 1978 (37)	In all-electric homes, NO ₂ levels were always lower than outside. Homes with electric stoves and gas furnaces showed lower indoor levels, but the difference was not as great.	Monitored houses were categorized in terms of type of heating and cooking device.
Moschandreas, et al. 1981 (38)	Residences with electric stoves had I/O ratios of 0.38, while homes with gas stoves had I/O ratios of 1.12.	Ten residences with gas and electric and smoking and non-smoking occupants were monitored.
Berk, et al. 1980 (39)	In a house with electric appliances, the I/O ratio was about 1. In a house with energy efficient appliances, the indoor NO ₂ levels were somewhat lower than those outdoors, although the reverse was found for NO. In a third home which had gas appliances, the indoor NO ₂ levels exceeded outdoor NO ₂ levels (I/O ratio >1).	Three experimental energy-efficient houses were monitored.

TABLE 4-4. SOME I/O STUDIES OF CARBON MONOXIDE

STUDY AUTHORS	SUMMARY OF RESULTS	CONDITIONS
Yocom, 1982 (35)	In the absence of indoor sources, the outdoor concentration pattern over long averaging times is a reasonably good prediction of indoor exposure.	Conclusions are based on a critical review of indoor-outdoor air quality studies.
Moschandreas, et al. 1981 (38)	Homes with electric stoves had average I/O ratios of 1.14.	Ten residences were monitored. There was a mix of gas or electric stoves and smoking and non-smoking occupants.
Berk, et al. 1980 (39)	Indoor and outdoor concentrations were comparable.	Measurements were made in energy-efficient homes.
Benson, et al. 1973 (40)	The data indicated that the I/O ratios were inversely related to outdoor concentration.	Based on the results of only two studies, one with relative low outdoor concentrations and the other with questionable monitoring methods.
Yocom, et al. 1970, 1971 (41,42)	The schedule for operation of mechanical ventilation systems and the introduction of outdoor makeup air can profoundly influence I/O ratios. After introduction of outdoor air containing high CO levels, the I/O ratio was much greater than unity for the whole day.	Makeup air was introduced into an air conditioned building during morning rush hours when outdoor CO levels were high.

TABLE 4-5. SOME I/O STUDIES OF CARBON DIOXIDE

STUDY AUTHORS	SUMMARY OF RESULTS	CONDITIONS
Moschandreas, et al. 1978 (37)	Indoor CO ₂ concentrations ranged from 150 to 2200 ppm while outdoor concentrations ranged from 100 to 500 ppm. Indoor levels correlated with occupancy and indoor activity patterns.	Concentrations were measured for a large group of residence types.
Berk, et al. 1980 (39)	Indoor concentrations always exceeded outdoor levels but were never over 2000 ppm.	Measurements were made in energy-efficient homes.
Moschandreas, et al. 1981 (38)	The indoor and outdoor ranges of hourly CO ₂ values were 296 to 2385 ppm and 262 to 776 ppm, respectively. Indoor concentrations varied with occupancy levels and air infiltration rates. Smoking and use of woodburning fireplaces or wood stoves had no discernible effect. Cooking with gas stoves had a direct effect on indoor levels. Indoor levels were higher in winter than summer.	Ten residences with gas and electric stoves and smoking and non-smoking occupants were monitored.
Berk, et al. 1981 (43)	In one home, weatherization retrofit produced a small increase in the I/O ratio but a small decrease was seen in a second house. Data showed a small impact on indoor CO ₂ levels in one house from smoking.	Measurements were made before and after energy conservation retrofits to homes.

TABLE 4-6. SOME I/O STUDIES OF SULFUR DIOXIDE

STUDY AUTHORS	SUMMARY OF RESULTS	CONDITIONS
Yocom, 1982 (35)	Outdoor concentrations over-predict indoor exposure by a factor of about 2.	Conclusions are based on a critical review of indoor-outdoor air quality studies.
Moschandreas, et al. 1981 (38)	Confirmed that I/O ratios varied inversely with outdoor concentrations.	Ten residences with gas and electric stoves and smoking and non-smoking occupants were monitored.
Benson, et al. 1972 (40)	I/O ratios varied inversely with outdoor concentrations. At high outdoor concentrations, the I/O ratio is relatively low, while at outdoor levels near the annual average ambient air quality standard (80 g/m ³), the I/O ratio appears to approach 1.0.	Reviewed available data.
Biersteker, et al. 1965 (44)	SO ₂ levels were lower indoors and the age of the house influenced the level; newer homes had lower levels.	
Anderson, 1972 (45)	I/O ratio ranged from 0.2 to 1.0.	Summarized existing data on I/O ratios for various countries from the mid-1950s.
Spengler, et al. 1979 (46)	SO ₂ indoor concentrations were 20 to 70 percent of the outdoor levels (I/O ratios 0.2 to 0.7).	SO ₂ levels were measured indoors and outdoors in six communities.

TABLE 4-7. SOME I/O STUDIES OF RESPIRABLE PARTICULATE MATTER

STUDY AUTHOR	SUMMARY OF RESULTS	CONDITIONS
Yocum 1982 (35)	In the absence of indoor sources, outdoor RSP will tend to under-predict indoor exposures. The chemical and physical nature of RSP may be quite different from that outdoors. Indoor sources, principally smoking, may produce I/O ratios in excess of 5.	Conclusions are based on a critical review of indoor-outdoor air quality studies.
Moschandreas, et al. 1978 (37)	Six residences with I/O ratios greater than 2 all had children 7 years old or less and all but one had smoking occupants. Eight homes had I/O ratios less than 1.0 and had no young children and little or no smoking. These results show an apparent influence on I/O ratios of indoor activity or other conditions related to small children.	RSP was measured by means of dichotomous samplers using virtual inspection, measuring particles 3.5 μ m and less in diameter.
Moschandreas, et al. 1981 (38)	Residences with and without smokers had average I/O ratios of 4.4 and 1.4, respectively. All of the residences with smokers had gas stoves, but one home with a gas stove and no smokers had an I/O ratio of 1.4 indicating that gas stoves appear to have little effect on indoor RSP levels. Use of fireplaces appeared to have an impact but no significant impact was noted from a basement wood stove.	Ten residences with gas and electric stoves and smoking and non-smoking occupants were monitored. Sampling was carried out using dichotomous samplers.
Berk, et al. 1981 (43)	Energy conservation retrofit increased the I/O ratio for the smoking situation and decreased it for the non-smoking situation. In a smoking house, the I/O ratio was 3.44 and after retrofit was 5.42. In non-smoking houses, I/O ratios were 0.64 and 1.94 and dropped to 0.39 and 1.33, respectively.	Three experimental energy-efficient houses were monitored.
Dockery and Spengler 1978 (47)	Indoor concentrations of RSP are related to outdoor concentrations; however, indoor sources such as smoking tend to overshadow the influence of the outdoor air. In areas of high outdoor levels, there was a tendency to close up the house which resulted in low I/O ratios. In three of the cities, the average RSP levels from air-conditioned homes were higher than outdoors--implying that the greater isolation from outdoors magnified the impact of indoor sources.	Reviewed the results from four cities to assess the importance of various factors on the RSP I/O ratio.
Spengler, et al. 1981 (48)	Differences in indoor RSP were significant. Smoking was one of the most important contributions to these differences. Average I/O ratios for the six cities were with no smokers--1.16, with one smoker--1.73, and with two or more smokers--3.34.	Levels were monitored indoors and outdoors in six communities.

TABLE 4-7. SOME I/O STUDIES OF RESPIRABLE PARTICULATE MATTER (CONTINUED)

STUDY AUTHOR	SUMMARY OF RESULTS	CONDITIONS
Knight and Humphreys 1984 (49)	RSP were collected on a secondary nucleopore filter contained in a stacked filter unit. An average RSP indoor to outdoor ratio of 2.3 was found.	Tests were conducted in an unoccupied test home having a low air infiltration rate of 0.39 ACH with a wood heater vented into a chimney.
Repace and Lowery 1980 (50)	In non-smoking settings, the I/O ratio was close to unity. A wide range of indoor values were obtained in smoking situations.	A sampler based upon the piezo-balance principle was used to investigate the I/O ratio relationship to smoking.

months, when outdoor SO_2 levels tend to be highest, the home is tightly closed against the cold and, therefore, indoor SO_2 concentrations will only be a fraction of those outdoors (35). Studies which look at indoor and outdoor concentrations suggest that the age of the house, infiltration rates, and seasonal variations in emissions are key factors that influence the concentration of SO_2 indoors. The type of fuel used in kerosene heaters and the reactivity of SO_2 can also affect the SO_2 concentration indoors and, therefore, the I/O ratio.

The RSP concentrations in homes are usually greater than outdoor concentrations even in the absence of significant indoor sources. The presence of smokers in a house can cause I/O ratios to reach levels over 5. Table 4-7 summarizes studies that have been conducted to investigate RSP I/O ratios. Several different methods are used for monitoring, so comparison of results from various studies should be made with caution.

Some indoor and outdoor monitoring for BaP has been conducted by GEOMET (38). In a house with a fireplace and smoking occupants, the indoor BaP concentrations were always above those outdoors. On one occasion when a fireplace was in use, the indoor concentration was almost 12 nanograms (ng/m^3), showing an unmistakable contribution from the fireplace, since outdoor concentrations were always less than $1 \text{ ng}/\text{m}^3$. In another house with a woodstove and no smokers, indoor BaP concentrations averaged $4.7 \text{ ng}/\text{m}^3$, nearly 5 times typical outdoor levels in urban areas.

Waldman, et al. studied the effect on homes of high ambient air pollutant levels caused by the operation of a foundry in the surrounding community (51). While it was apparent that indoor inhalable particle sources (such as smokers) strongly affected indoor concentrations, the influence of the ambient concentrations could be discerned, especially in the cleaner homes.

HOUSE VOLUME AND RATE OF MIXING

Combustion-generated pollutants in a residence usually emanate from stationary sources. However, sources such as tobacco smoke or portable space heaters may result in emissions in any room of a house. The locations and strengths of sources will influence pollutant concentrations in individual rooms and throughout the house. In general, short-term peak concentrations occur in rooms generating the pollutant, but within a relatively short period of time, a matter of minutes or for up to a few hours, concentrations are usually relatively uniform throughout a house. If pollutants are confined to the room in which they are produced, they will build up to higher concentrations than if they are dispersed throughout the house. The larger the volume over which a given quantity of pollutant is distributed, the lower the concentration.

The interior design of a house affects the concentrations of pollutants throughout the house. The division of the interior of a house by walls and partitions causes resistance to the dispersion of pollutants. The location of interior doors and stairways provides the pathways of least resistance for air movement. Heights of rooms can affect the degree of stratification which may occur and the associated build-up of pollutants in stagnant layers (27).

The dispersion of air pollutants throughout a residence is the result of diffusion and mixing induced by free and forced convective air movement. Diffusion is the movement of pollutants by natural molecular motion from regions of higher concentrations to regions of lower concentrations. Pollutants will become dispersed by diffusion even if the air is stagnant. However, microscopic air movement (convection) is a major mode of transport of pollutants throughout a house. Driving mechanisms which generate air currents include air infiltration, ventilation, temperature differences causing convective movement, pressure differences created by outside winds, air circulation fans in heating and cooling systems, and even movement of inhabitants.

Internal air movement is important to the distribution of contaminants within a building. Diffusion is a relatively slow process which would result in large gradients of pollutant concentrations in the absence of convection. On the other hand, forced central air systems, such as forced air furnaces, circulate air throughout the entire house and tend to provide extensive mixing, resulting in nearly equal concentrations throughout a residence. Decentralized systems, such as baseboard heaters and room air conditioners, recirculate air within individual rooms so pollutants are less likely to be distributed to other rooms (27). Non-uniform concentrations can also result from variations in the air exchange between individual rooms and the outside atmosphere.

Experimental studies have been conducted to determine if indoor zones with distinct pollutant patterns exist and to determine if sampling from one monitoring zone is sufficient to characterize the air quality of an entire house. A number of studies, as discussed below, have indicated that the location of the source can influence the distribution of combustion-generated pollutants throughout a house and that the concentrations of pollutants throughout a house are generally time dependent.

Using a continuous sampling system, Moschandreas and Zabransky monitored three zones in office buildings and the kitchen, bedroom, and activity room in residences (52). A statistical analysis of variance was performed among the three indoor zones using hourly average pollutant concentrations. The results for NO_2 are presented in Table 4-8. The following conclusions were drawn from this inter-zonal study for gaseous pollutants:

- Pollutants with strong indoor generation are observed to have inter-zonal statistical differences in gas cooking residences and offices, but not in electric cooking residences, where, in general, the observed differences in the magnitude of the pollutant concentrations are not large.
- One indoor sampling zone is not sufficient to specify indoor pollution concentration maximums in residences having indoor sources of pollution.
- While more than one zone would be preferable, hourly pollutant concentrations obtained from one indoor zone adequately characterize the indoor environment.

TABLE 4-8. INDOOR ZONAL ANALYSIS OF VARIANCE FOR THE MEANS OF HOURLY NO₂ CONCENTRATIONS (ppb)^a

SITE ^b	MEAN OF HOURLY CONCENTRATIONS OVER THE ENTIRE SAMPLING PERIOD			MAX. INTER-ZONAL DIFF. OF MEANS
	KITCHEN (2)	BEDROOM (3)	LIVING ROOM (4)	
R1G	27.1	19.2	21.8	e 7.9
R2E	--	--	--	
O3 ^c	17.9	17.3	16.7	1.2
R4G	24.7	22.0	27.7	e 5.2
R5E	--	--	--	e
R6E	--	--	--	
R7G	--	21.5	--	3.0
R8G	28.7	18.3	20.6	10.4
O9 ^d	--	--	--	e
R10G	--	30.6	--	7.1
R11G	--	23.6	--	e 5.4
R12E	--	--	--	
R13G	48.3	28.7	35.9	19.6
R14G	41.0	20.6	26.2	20.4

^a The mean NO₂ concentration is indicated for only those zones that differ significantly from other indoor zones.

^b R--Residence; O--Office; E--Electric; G--Gas. Number indicates the order in which buildings were sampled.

^c O3: Zone 2--Open Office, Zone 3--Xerox Room, Zone 4--Conference Room

^d O9: Zone 2--Print Shop, Zone 3--Conference Room, Zone 4--Office Room

^e Means do not differ significantly.

Source: Moschandreas, D.J. and J. Zabransky, "Special Variation of Carbon Monoxide and Oxides of Nitrogen Concentrations Inside Residences," presented at the International Symposium on Indoor Air Pollution, Health and Energy Conservation, 1981.

- Given the mean 24-hour concentration, the maximum indoor hourly concentrations for CO, NO, and NO₂ can be estimated for electric residences. Owing to the increased scatter in the paired data points, the reliability of similar estimates in residences with gas facilities is reduced.

Maldonado and Woods performed tests to evaluate the uniformity of mixing in a building at the Iowa State University Energy Research House, located in Ames, Iowa (53). The decay of a tracer gas (SF₆) was monitored after being uniformly distributed and after injection in specific rooms. The house layout is shown in Figure 4-12. The results of the monitoring tests are illustrated in Figures 4-13 through 4-15. The observations and conclusions resulting from the experimental studies are summarized below.

- Although rates of decay of SF₆ varied from test to test because of different wind and outdoor temperature conditions, all tests resulted in similar patterns.
- To evaluate ventilation efficiencies, a uniform concentration of tracer was established and then allowed to decay. Zones where more outdoor air is introduced showed a faster decay. The bedrooms had the lowest ventilation efficiencies and the greenhouse had the highest.
- A typical decay distribution is shown in Figure 4-14. When a central air handling system is operated, uniform concentrations of SF₆ were maintained throughout the house during the decay process (see Figure 4-15).
- When the tracer gas was released in the southeast bedroom, one of the rooms which had the lowest ventilation efficiencies (measured during the lowest reported average wind speed), little transport occurred to other zones because of the limited air movement, which is inherently associated with low ventilation efficiencies.
- The results showed that normal rectangular shaped rooms had only small variations in concentrations among different points (53 percent). Rooms with irregular shapes and high ceilings showed larger variations with higher concentrations at the upper floor than at the lower floor (i.e., stratification was found in all rooms that spanned more than one level in the building) (see Figure 4-14). They concluded that individual rectangular rooms with normal ceiling heights can be treated as uniformly mixed for practical purposes when compared to room-to-room and whole-house differences.

Figure 4-12. Floor Plan of the Iowa State University Energy Research House

Source: Maldonado, E.A.B., and J.E. Woods, "A Method to Select Locations for Indoor Air Quality Sampling," presented at Harvard University Indoor Air Quality Conference, 1983.

Figure 4-13. Concentrations of SF_6 Following Tracer Release in Living Room

Source: Maldonado, E.A.B., and J.E. Woods, "A Method to Select Locations for Indoor Air Quality Sampling," presented at Harvard University Indoor Air Quality Conference, 1983.

Figure 4-14.

Concentrations of SF_6 During Uniform Mixing Test

Source:

Maldonado, E.A.B., and J.E. Woods, "A Method to Select Locations for Indoor Air Quality Sampling," presented at Harvard University Indoor Air Quality Conference, 1983.

Figure 4-15.

Concentrations of SF_6 with Central Air Fan Energized

Source:

Maldonado, E.A.B., and J.E. Woods, "A Method to Select Locations for Indoor Air Quality Sampling," presented at Harvard University Indoor Air Quality Conference, 1983.

- In the room where the tracer gas was released, the concentration increased to a high level immediately after the release, then decreased rapidly as the tracer gas moved to other rooms and outdoors.
- In the other rooms, the rise in concentration took a longer time, and the time increased as the distance between the room and the point of release increased. In some cases (see Figure 4-13), it took up to five hours for the other rooms to reach their peak concentrations.
- In most cases, the highest risk zone is either the location where a contaminant is generated or one of the zones with the lowest ventilation efficiencies in the building.

Other experimental studies have resulted in the following observations:

- Both Moschandreas and Spengler and their co-workers found a pronounced increase in the NO_2 concentrations in some kitchens in gas-cooking homes (38,54). Moschandreas, et al. found that on the average, kitchen concentrations were twice those in bedrooms in homes that had gas stoves (38). Spengler, et al. found kitchen NO_2 levels in homes with gas stoves were about $50 \mu\text{g}/\text{m}^3$ higher than outdoor levels, and NO_2 levels were about $4 \mu\text{g}/\text{m}^3$ lower than outdoor levels in electric-cooking homes (54).
- Moschandreas and Ozkaynak and their co-workers found large fluctuations in measured concentrations of tracer gas throughout various rooms of a house within relatively short periods of time, but equilibrium was reached within an hour (38,55).
- Traynor and co-workers found that the rate of mixing is dependent on the air exchange rate. Inside the Energy Efficient Buildings research house, at 0.13 ACH, pollutant concentrations at three locations in the house were within 10 percent of each other 24 minutes after a gas stove was turned off. At 0.33 ACH, it took about an hour, and at higher rates, it was hours before equilibrium was reached (6,7).
- Wade and co-workers found that concentrations of pollutants were more uniformly distributed in the various rooms of a house in colder weather when the house was closed up more often (56).
- Ju and Spengler investigated room-to-room variations in concentrations of respirable particles and found that there is generally good mixing; however, inter-room differences can occur due to smoking, ventilation differences, and localized sources (57).
- Ozkaynak, et al. reviewed data on indoor/outdoor pollutant and tracer concentrations and conducted special studies within a

kitchen to determine the vertical and horizontal variability of pollutant and tracer gas concentrations (55). Within 2-3 minutes after injection of tracer gas, the concentrations in all positions reached a peak and then declined sharply. Strong mixing patterns and the near uniformity of concentrations measured during a stove-on experiment suggested that convection and/or thermal turbulence associated with strong temperature gradients over the stove provide rapid mixing and flow patterns. However, large fluctuations in the measured concentrations occurred within relatively short periods of time.

- Sexton, et al. conducted an indoor/outdoor monitoring study for respirable particles in Waterbury, Vermont (31). They found significant room-to-room differences in homes with unvented kerosene heaters; however, respirable particles were relatively well mixed inside both wood- and non wood-burning residences.

In a project sponsored by GRI, Mehegan, et al. reported preliminary results of a multi-phase pilot survey being performed to quantify systematically various factors that may affect NO_2 concentrations among residences with gas ranges (58). They found that single and multi-story homes appear to be two distinct subgroups requiring separate analytical treatment to discern the most important factors related to indoor NO_2 variations.

Baker, et al. and Wilson, et al., in documenting results from an identical study, reported the following observations regarding the effect of house volume and rate of mixing on indoor NO_2 concentrations (2,59):

- Average indoor NO_2 concentrations were found to have an inversely proportional relationship to home size.
- On average, bedroom NO_2 levels were found to be lower than outside NO_2 levels, and indoor kitchen levels were found to be higher than outside NO_2 levels.
- Older and newer homes were found to be associated with higher NO_2 and lower NO_2 levels, respectively.
- Contrary to previously held suppositions, findings revealed that on average, homes with lower air exchange rates (tighter homes) were more likely to be associated with lower NO_2 levels than homes with higher air exchange rates in the Southern California Gas Company service area.

These findings suggest the importance of a large house volume in diluting and/or providing large reaction surfaces for NO_2 removal, and that outdoor sources of NO_2 may be significant in the area covered by this study (60).

Statistical analyses performed by Goldstein, et al. suggested a strong relationship between NO_2 levels at different locations with the same home (61).

REACTIVITY

In many homes with indoor pollutant sources, the concentrations of some pollutants are lower than those of the ambient (outdoor) air. This suggests that interior materials remove pollutants from indoor air. Mechanisms by which this process occurs have been postulated as follows:

- Adsorption--Adsorption is the process by which ions or molecules present in one phase tend to condense and concentrate on the surface of another phase. There are three general types of adsorption: physical, chemical, and exchange adsorption, depending on the forces acting between the surface and the chemical being adsorbed.
- Absorption--Absorption is the dissolving of one or more soluble components of a gas mixture in a liquid, or the diffusion of gaseous or liquid materials into solids. This may be a physical phenomenon or may involve solution of the material in the liquid followed by reaction with one or more constituents in the liquid solution.
- Conversion--Pollutants may be converted to other compounds through chemical reactions such as oxidation or reduction.
- Deposition--Particles settle or vapors condense onto indoor surfaces.

A summary of the indoor combustion-generated pollutants whose concentrations may be significantly affected by these reactions is given below.

- Nitrogen Oxides--NO₂ is removed by chemical conversion in both the gas phase and at surfaces. NO is less chemically reactive indoors, but NO may also be adsorbed on surfaces indoors (62,63,64).
- Carbon Monoxide--CO is comparatively inert; however, it may be adsorbed on surfaces indoors (29,64).
- Particulate Matter--Particulate growth and chemical transformation occur through gas-particle and particle-particle interactions (29). Particulate matter will deposit on surfaces indoors.
- Sulfur Dioxide--SO₂ concentration may be reduced due to the oxidation of SO₂ to sulfate particles or by dry deposition on surfaces. SO₂ interacts with airborne particles primarily by adsorption (11,65).

A number of factors will affect the rate at which reactions occur indoors, which will, in turn, affect the rate of removal of pollutant concentrations. Factors which influence reactivity include:

- Surfaces--Some air pollutants differ in stability between outdoors and indoors because of the variety of surfaces found indoors on which reactive compounds adsorb and decompose. For example, ozone is decomposed especially quickly indoors. This is also somewhat true for SO_2 and NO_2 , while CO and NO are less reactive.
- Moisture--The moisture in the air can enhance pollutant deposition rates. This is true for gases such as SO_2 and ozone (63).
- Temperature--The rates of most chemical reactions increase with temperature. In general, the rate of a reaction will roughly double for each 20°F (10°C) rise in temperature (66).
- Presence of Other Compounds--Reactions are affected by the presence or absence of certain compounds (55,62).
- Solar Radiation--Some reactions require the presence of sunlight. For example, the decomposition of NO_2 to NO and O_3 requires sunlight (62).

Some experimental studies have been conducted to determine if pollutant removal due to reactivity is significant. Leaderer conducted emission tests for kerosene heaters in an environmental chamber and found no measurable removal of CO, NO_2 , and SO_2 by the chamber surfaces (67).

Cain and Leaderer conducted tests during smoking and non-smoking occupancy in a controlled environmental chamber (68). For CO, ventilation rate appeared to be the only removal mechanism. However, for total suspended particles (TSP), they concluded that surfaces in an enclosed room seem to be important sinks for tobacco smoke indoors, thus increasing the effective removal rate. This removal rate depends on the type of surface, mixing rate, ventilation rate, and recirculation rate.

Some models used for predicting indoor pollutant concentrations require quantification of the pollutant removal rate due to reactivity. For example, Traynor, et al. used an indoor air quality model and experimental data to determine pollutant reactivities (69). The values obtained indicate that the pollutant reactivity can be, in some cases, as important as air exchange rate in removing indoor pollutant concentrations, especially when the air exchange is low. The average values for pollutant reactivities were 0.15 hr^{-1} for NO_x (as N), 0.23 hr^{-1} for SO_2 , 0.40 hr^{-1} for HCHO, and 0.48 hr^{-1} for particles less than $0.5 \mu\text{m}$.

Ozkaynak, et al. collected data on indoor-outdoor pollutant and tracer concentrations and developed a model to predict pollutant concentrations, taking into account the reactivity of pollutants, since the role of reactive chemistry becomes important in the prediction of peak levels of some pollutants (55). The simplified NO_x chemistry was incorporated into the model using the interaction of NO, NO_2 , O_3 , and $\text{O}(^3\text{P})$ in the following reactions.

The first equation represents photolysis of NO_2 . J is the photolysis rate. The heterogeneous loss rate constant is the result of processes such as deposition, reaction with surfaces, and other pseudo-first-order reactions. Mathematical methods were utilized to estimate these rate constants. The photolysis rate ranged from 0.018 hr^{-1} to 1.02 hr^{-1} , and averaged 0.41 hr^{-1} . The heterogeneous loss rate for NO ranged between 0.02 hr^{-1} to 0.27 hr^{-1} , and averaged 0.12 hr^{-1} , and for NO_2 ranged between 0.01 hr^{-1} and 0.5 hr^{-1} , and averaged 0.28 hr^{-1} .

GRI sponsored several projects designed to measure the effect of surfaces in removing NO_2 from indoor air. The following conclusions have been reported by various investigators in this effort:

- Yanagisawa studied the rate and capacity of various typical interior materials of construction in removing NO_2 from air (20). Several commonly used building materials (i.e., cement, gypsum board, and masonite) were packed into glass tubes, then exposed to an air stream containing known concentrations of NO_2 . During the experiments, temperature, relative humidity, and air flow rate were maintained at constant levels. The adsorption rate and adsorption capacity for NO_2 were determined by sampling the air stream after it passed over the building material.
- Billick and Nagda also measured reaction decay of NO_2 , and determined that the reactivity of different materials vary from 0 to 8 hr^{-1} or more, that the effects of humidity on reaction decay were inconsistent, that the longer the duration of the appliance emitting the NO_2 , the smaller the decay constant, and that the production of NO sometimes accompanies the decay of NO_2 (21). Table 4-9 presents some data from the study.
- Spicer, et al. investigated the rates and mechanisms of the NO_2 removal process and concluded that there was a need to include sink terms in indoor air models dealing with NO_2 (70). Figure 4-16 shows the removal rate constants for typical indoor materials. Preliminary results of this study suggested that both rate and capacity are strongly affected by relative humidity.
- Gundel, et al. studied the effects of adding activated carbon (a substance with a large surface area to volume ratio) to rooms with elevated NO_2 concentrations in order to investigate the effects of surface area on the rate of NO_2 removal (22). It was observed during these experiments that activated carbon particles reduce the level of NO_2 and raise the level of NO . It was concluded from these observations that surfaces do have the potential of influencing NO_2 concentrations.

TABLE 4-9. NO₂ REMOVAL RATES MEASURED IN A STEEL CHAMBER FOR SELECTED TYPES OF RESIDENTIAL MATERIALS

I. <u>Highest Removal ($\geq 6 \text{ hr}^{-1}$)</u>	II. <u>High Removal ($3.7\text{-}4.2 \text{ hr}^{-1}$)</u>
<ul style="list-style-type: none"> - Unpainted plasterboard (>8.4) - Cement block (8.4) - Wool carpet (6.0) 	<ul style="list-style-type: none"> - Used bricks (4.2) - Masonite (4.1) - Polyurethane foam (3.7)
III. <u>Moderate Removal ($1.9\text{-}2.7 \text{ hr}^{-1}$)</u>	IV. <u>Low Removal ($<1 \text{ hr}^{-1}$)</u>
<ul style="list-style-type: none"> - Cotton/polyester bedspread (2.7) - Painted plasterboard (2.6) - Plywood (1/4 in) (2.5) - Acrylic fiber or nylon carpet (1.9-2.0) - Ceiling tile (wood fiber) (1.9) - All vinyl wallcovering with paper backing (1.9) 	<ul style="list-style-type: none"> - Particle board (0.7) - Ceramic tile (0.7) - Cotton terry-cloth (0.3) - Wool (80%)/polyester (20%) fabric (0.3) - Window glass (<0.1) - Galvanized metal duct (0) - Formica counter-top (0) - Vinyl or asphalt tile (0)

Source: Billick, I.H. and Niren L. Nagda, "Reaction Decay of Nitrogen Dioxide," Indoor Air '87: Proceedings of the 4th International Conference on Indoor Air Quality and Climate, Volume 1, pp. 311-315, Institute for Water, Soil, and Air Hygiene, Berlin, 1987.

Figure 4-16. Removal Rates for Various Materials

Source:

Spicer, C.W., et al., "Rates and Mechanisms of NO₂ Removal from Indoor Air by Residential Materials," Indoor Air '87: Proceedings of the 4th International Conference on Indoor Air Quality and Climate, Volume 1, pp. 371-375, Institute for Water, Soil, and Air Hygiene, Berlin, 1987.

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Section 5

INDOOR CONCENTRATIONS

INTRODUCTION

The monitoring of indoor air pollutant concentrations is performed to accomplish a number of important goals. Data obtained in large-scale studies involving many homes provide a basis for estimating the exposure of large populations to indoor air pollution which in turn, help identify problem homes so that appropriate control measures may be undertaken. Monitoring studies performed in the laboratory or under carefully selected field conditions provide valuable insight into source emission rates as well as the factors which determine the dynamics of indoor air quality. In addition, the characteristics of and the usage patterns of occupants within certain homes in the housing stock which may be creating indoor air quality problems can be identified by monitoring studies.

Monitoring studies vary in their scope and level of detail. Some studies employ an environmental chamber designed to simulate actual indoor environments in order to determine the impact of source emissions on indoor concentrations. Other studies involve measurements of combustion pollutants within occupied residences to interpret the impact of actual operating conditions and temporal and spatial variations on indoor air quality. In an attempt to understand the total exposure of humans to pollutants, simultaneous measurements of indoor and outdoor air quality, and the use of personal monitors have been conducted.

When reviewing the results of monitoring studies, it is important to identify similarities/differences in the experimental conditions and protocols. For example, the location of a sampler, i.e., its distance from the emission source, affects reported concentrations. Certain instrumentation can measure peak concentrations of pollutants, while for other studies weekly or annual averages are provided. The experimental controls and variables, such as infiltration rate, source controls, and operating conditions, should be noted when making data comparisons.

Modeling is sometimes employed in conjunction with monitoring or laboratory studies as a means of extrapolating data. For example, monitoring or emissions data can be used as inputs to models which predict the change in pollutant concentrations over time or evaluate the influence of varying air exchange rates on indoor pollutant levels. Models can apply monitoring data from a particular sample of residences to make more general conclusions regarding exposures of a larger population.

This section discusses methods used to measure and monitor indoor air quality. It reviews the results of monitoring studies which have sought to quantify the contribution of combustion sources to indoor air pollution and to the overall exposure of humans to combustion-related pollutants. It also describes the monitoring methods and instrumentation techniques commonly employed in the field and their most appropriate applications.

MONITORING TECHNIQUES AND INSTRUMENTATION

The methods, techniques, and instrumentation used to monitor indoor air quality depend on the scope and objectives of the monitoring program. Pollutant levels can be measured by measurement techniques which vary from simple and inexpensive passive collection devices to sophisticated, expensive real-time detection equipment. Data collection techniques range from mail-out surveys to fully-instrumented laboratory test chambers. The most appropriate method will depend on factors including cost, accuracy, precision, and types of data required, and the number of sites at which data are to be collected.

A summary of some commercially available instrumentation techniques is presented in Appendix A.

Continuous Monitoring

Continuous monitoring of pollutants is the frequent measurement of indoor air pollutant concentrations over a specified time interval. This technique provides information on the time variation of pollutants within an enclosed space in order to either study the probable factors influencing the generation and/or concentration of pollutants or to provide data on peak short-term concentrations as well as average concentrations. Continuous monitoring also provides a basis for calculating the same types of information provided by integrated monitoring (discussed below).

The use of continuous monitoring in indoor air pollution research is limited by the relatively high cost of purchasing and operating the equipment. In addition, the potential safety, heat, and noise problems may prohibit its use in the residential indoor environment. Continuous monitoring is best suited for a single remote site such as a laboratory or other applications where intensive data collection and analysis are to be performed at a limited number of sites.

Continuous monitors are available for most major indoor air pollutants of interest, including CO, NO, NO₂, and SO₂. A representative listing of some of the manufacturers of continuous monitoring equipment is shown in Appendix A; additional information is provided by Cox, et al. (1).

Integrated Monitoring

An integrating monitor is a device that collects a single sample at a known sampling rate over a specified period--ranging from one day to several weeks or months. Collection may be by passively adsorbing the contaminant or by actively pumping the air through the monitor. The monitor is then analyzed, either at the collection site or in a laboratory, to determine a single value which represents the long-term average concentration during the sampling period. It is used when the mean concentration is either desirable or adequate for the purpose. A variety of pollutants, including particles, gases, and vapors are sampled by this technique.

Integrated samples are advantageous in that they are less expensive and require less manpower than continuous monitors. They can be used to measure concentrations that are too low to be measured by other techniques. Samples can

often be analyzed later at a more convenient time or place, and average concentrations over long periods are easily obtained. However, measurements of short-term temporal variations are not attainable: only with frequent sampling can temporal variability in concentrations be assessed.

In recent years, integrated sampling has been commonly used in larger monitoring studies because of the low cost per sample and the usefulness of the integrated sampling technique in screening large numbers of homes. Many of the currently available passive-integrating monitors were originally developed for occupational uses, and thus are often designed to measure higher levels of indoor pollutants than those normally found in the residential setting. To address this issue, EPA is currently developing more sensitive passive integrating samplers (2).

Grab Sampling

Grab sampling involves the collection of one sample over a very short period. It may simply involve filling a container with an air sample for analysis at a laboratory, or it may involve extractive sampling, as in colorimetric detector tubes. Grab sampling provides quick results, which show the short-term average (or possibly instantaneous) concentration of the air sampled. It is the least expensive technique for field sampling, unless very frequent samples are required, as would be the case if pollutant concentration changes versus time were to be assessed.

Grab sampling, with its low per-sample cost and minimal manpower requirements, is suitable for large-scale survey work, but a number of restrictions are associated with this technique. No information other than an "instantaneous" concentration can be obtained. Although a sample can be taken under specific known conditions and will reflect contaminant levels under those conditions, the conditions at a given moment may not accurately reflect the average levels to which residents are exposed over a day, month, or season. In addition, sampled volumes are relatively small, and the laboratory measurement technique must be sensitive enough to determine ambient concentrations directly. Quality control is difficult to maintain, but must be established before this technique can be used with confidence (3). Despite these limitations, grab samples are often useful for screening homes for specific contaminants, and serial, or repeated, grab samples over time may reflect indoor air quality.

Personal Monitors

As attention has focused on the assessment of total exposure to pollutants (i.e., outdoor, indoor, in-transit), a wide variety of miniaturized air samplers has become available that collect gaseous and particulate samples from the immediate vicinity of people. These samplers fall into two categories: passive (based on membrane permeation or diffusion through a geometrically defined air space) and non-passive (in which air-pumping devices draw defined air volumes through devices of known collection efficiency).

Passive samplers use the kinetic energy of gas molecules and the efficiency of the absorbent collector to extract pollutant molecules from the air at a known rate. The samplers must be placed at the collection site, but have no

requirement for a pump, flow regulators, or batteries, and are often attached to individuals to assess individual exposure. Such samplers, therefore, have major advantages with respect to weight, cost, and maintenance. There are two basic types of passive monitors: diffusion and permeation.

The diffusion collector technique requires that an efficient collecting medium be placed at one end of a tube and that the other end of the tube be exposed to the contaminated atmosphere. The rate of transfer of the test gas to the sampling reagent is determined by the coefficient of diffusion of the gas, the ambient concentration of the gas, and the dimensions of the tube. In principle, this method is applicable to determination of any gaseous air pollutant for which an efficient, selective absorbent is available, for which the coefficient of diffusion of the gas in air is known, and for which an appropriate analytic chemical procedure may be devised. Diffusion samplers have been used for water vapor, CO, NO, NO₂, and SO₂ (3).

A large variety of permeation samplers used for monitoring systems are available commercially. All use membranes fabricated and calibrated to control the rate of permeation of the pollutant to the collector. Processing of the collected sample varies widely; chromatographic (CG) or colorimetric procedures are commonly applied for measurement. Commercial monitors are available that allow determination of more than 80 compounds by this method. Chlorine, vinyl chloride, NO₂, SO₂, alkyl lead, and benzene have been determined. The utility of a spectrum of absorbents in these passive collectors has been tested (3).

Large numbers of active samplers, which use pumps to move the air, have come into use over the last two decades. An example of an active, or non-passive, personal monitor is a recently developed pump that is positioned next to the wearer's diaphragm by a light harness. The volume of air pumped by the motion of the wearer's thoracic cavity is recorded by an electronic package, which may be checked by a detached readout system. This system samples air for gases through coated diffusion-tube collectors or for particles through small filters at flow rates of 75-500 milliliters/minute, depending on the wearer's breathing rate. The complete apparatus weighs 590 grams. In conjunction with spirometer calibration, actual exposures to measured pollutants may be calculated (3).

Particulate samplers use a pump to take in an air sample and to separate the respirable-particle fraction. The relatively low power available to drive the air-sampling pump usually limits particle collection by personal monitors to filtration, either in a single stage or in a second stage that follows a cyclone (which collects the large, non-respirable particles). For respirable particle sampling, the air-flow rate must be precisely controlled.

Infiltration Measurement Techniques

As discussed in Section 4, Factors Affecting Pollutant Concentrations, the infiltration rate of a residence affects the degree to which outdoor contaminants enter a building and indoor contaminants accumulate and disperse throughout a residence. Most field monitoring programs require measurements of the infiltration rate to determine its influence on indoor concentrations.

There are two fundamental approaches to the measurement of air infiltration and air leakage in buildings. Ambient air infiltration is measured using tracer gas techniques, while the airtightness of a building is measured by artificially pressurizing the building and measuring the induced air flow rate. Each approach provides substantially different building air loss information and it is not normally possible to directly interchange the results. The tracer gas technique gives a direct measure of air infiltration rate corresponding to the climatic conditions prevailing at the time of test; many successive measurements over an extended period of time are necessary to determine the relationship between the rate of air infiltration and weather conditions for any particular building. On the other hand, the pressurization technique is usually performed at pressures in excess of ambient conditions and, consequently, the results are independent of weather conditions.

By far, the most commonly used method of estimating air-exchange rates is the tracer-gas decay technique (3). In this method, a tracer gas is released into the building space at one or more points, possibly with the use of mixing fans, to produce a uniform concentration throughout the building space. The tracer gas source is then removed. If homogeneity is maintained, the decay rate of the tracer gas is exponential, and the infiltration rates can be determined by sampling the air at several times.

An alternative approach is to maintain a constant concentration, so that the infiltration rate becomes directly proportional to the tracer gas injection rate. A constant concentration can normally only be maintained by using automatic control techniques.

Air infiltration measurements can also be made by releasing tracer gas at a constant rate. With perfect mixing, the indoor concentration will reach a steady-state value. From this and the injection rate, a "time-averaged value for the infiltration rate can be calculated. With this technique, although it is simple to perform, it often takes many hours to reach steady-state equilibrium. The constant emission approach has useful applications in estimating long-term, time-averaged infiltration.

The success of the tracer gas techniques is dependent on the validity of four key assumptions; these are as follows (4):

- The tracer gas should be non-reactive.
- The mixing of tracer gas should be perfect and instantaneous.
- The effective volume of the enclosure should be known (decay, constant emission, and constant concentration methods).
- The factors that influence air infiltration should remain unchanged throughout the measurement/integration period (decay and constant emission methods).

The main disadvantage of the tracer gas method outside of the laboratory is that single measurements are generally of little value. It is, therefore, not possible to use this method to make a rapid check on building air exchange rates under ambient conditions. The effort involved in making many measurements has been alleviated to some extent by the introduction of automatic tracer gas methods; however, these methods involve a substantial increase in the complexity of instrumentation. The second main criticism of tracer gas methods is that the mixing necessary to ensure that the tracer gas is thoroughly distributed creates artificial conditions that may influence the results. Despite these problems, however, the tracer gas technique offers the only real method of measuring the naturally occurring fresh air change rate in a building (4).

Whole building pressurization provides the main alternative to tracer gas analysis and, because it is a relatively much more straightforward test to undertake, has become very popular. Furthermore, leakage measurements are normally made above the ambient pressure regime and, therefore, the results are independent of weather conditions. The test is further simplified by the ready availability of commercial pressure testing equipment suitable for use in dwellings (4). In some countries, new residential buildings must conform to specified levels of airtightness, while in others, the pressurization technique itself is the subject of national standards. Measurements are made by using a suitably rated fan to create incremental pressure differences between the interior and exterior of the building in the ± 10 -100 Pascal range. For each pressure increment, the corresponding air flow rate through the fan is measured. Frequently, the instrumentation is built into a door (blower door) which temporarily replaces an existing entrance to the building.

Residential Monitoring Services

As awareness and concern regarding the deterioration of indoor air quality heightens, some homeowners may wish to measure the air quality within their homes. Homeowners may purchase inexpensive single-use devices that detect specific peak contaminant concentrations (e.g., CO at 50 ppm) by registering a color change when a specific level is reached or exceeded. Passive sampling devices may be purchased or rented and returned to a laboratory for analysis to determine time-weighted average concentrations. Another option is to enlist the services of laboratories, private companies, or institutes which monitor contaminant levels in homes. Some of these organizations provide both diagnostic and remedial services, including measuring concentrations and ventilation rates, determining maximum likely values, identifying sources and problems, and recommending corrective actions such as equipment modification or heat exchanger requirements.

Currently, the cost of measuring five common pollutants using passive monitors is several hundred dollars. These costs may drop if the demand for such services increases. One monitoring company points out that these costs are not disproportionate to other costs borne by homeowners, such as renovating a bathroom, or the amount spent annually on health care (5).

MONITORING PROGRAMS AND RESEARCH RESULTS

This section summarizes the results of monitoring studies which have measured the effect of specific indoor sources of combustion products on indoor

air quality. The emphasis is on residential buildings; however, some studies reported here have included a variety of structural types. Table 5-1 is a tabulation of maximum pollutant concentrations reported by various researchers with respect to specific pollutant sources. In general, the data presented represent situations whose characteristics are specific to the site, the experimental design, and the combination of activities that produced the effects. The experimental conditions should be noted when comparing data from different studies or in developing any applications or conclusions based on the data presented here. The reader is encouraged to use the reference section at the end of this chapter if further details regarding specific studies are required.

Kerosene Heaters

The use of kerosene heaters for supplementary heat represents a potential source of pollutants in the indoor environment. The use of "new generation" (improved technology) kerosene heaters has increased dramatically since their introduction in the United States in the mid-1970s. The estimated number of kerosene heaters in use at the end of 1987 was approximately 5.3 million (6). As shown in Figure 5-1, most of these units were in the South with the smallest amount in the West. Approximately 5.8 percent of all U.S. households have kerosene heaters.

Field monitoring and laboratory studies that evaluate the emissions from kerosene heaters typically involve a variety of heater designs. A discussion of the basic characteristics of various types of kerosene heaters is included in Section 3, Emissions from Combustion Sources.

Researchers at the Lawrence Berkeley Laboratory (LBL) tested unvented kerosene heaters in a well-mixed 27 cubic meter (m^3) environmental chamber (7,8). After one hour of operation, the levels of NO , NO_2 , and CO_2 were higher than the recommended ASHRAE guidelines for indoor air (Figures 5-2 and 5-3). It should be noted that the heaters used in these studies were over-sized for the size of the chamber. In October 1982, Consumer Reports published modeling results based on the LBL studies that projected concentrations of CO_2 , NO_2 , and SO_2 far in excess of the recommended ASHRAE guidelines, which resulted in litigation with the kerosene heater industry. The results of the laboratory studies and modeling efforts such as these have prompted a number of monitoring studies to assess the actual pollutant levels resulting from the residential use of unvented kerosene heaters. These are discussed below.

The Consumer Product Safety Commission (CPSC) also evaluated information concerning the emissions, modeling, and health effects of pollutants emitted by kerosene heaters (9). Preliminary home monitoring data were obtained from two field studies. Kero-Sun, Inc. contracted with Weston Designers and Consultants to monitor a single occupied dwelling for CO , CO_2 , NO_2 , SO_2 , and oxygen. The second study, performed under contract to CPSC by the Pierce Foundation, involved 130 homes with kerosene heaters and 190 homes without heaters. A comparison of the range of pollutants found in the two field studies indicates good agreement (see Table 5-2).

TABLE 5-1. SELECTED RESULTS DOCUMENTING EFFECTS OF SPECIFIC POLLUTANT SOURCES

SAMPLE	MAXIMUM CONCENTRATIONS OBSERVED							
	NO ₂ (ppb)		CO (ppm)		RSP ($\mu\text{g}/\text{m}^3$)		SO ₂ (ppm)	
	PEAK	AVERAGE	PEAK	AVERAGE	PEAK	AVERAGE	PEAK	AVERAGE
Kerosene Heaters								
Girman, et al. 1982 (7)	1900	--	15	--	--	--	--	--
CPSC 1933, (9)								
1 Home	--	380	--	25.3	--	--	--	0.10
13 Homes	--	310	--	19.0	--	--	--	0.65
Ritchie and Oatman, 1983 (12)^a								
Townhouse	130	110	7	6	--	--	0.12	0.102
Ryan, et al. 1983 (13)								
1 Home	--	160	--	--	--	--	--	--
Leiderer, et al. 1984 (10)								
Over 150 Homes	--	40.8	--	--	--	--	--	0.06
Parkhurst, et al. 1988 (14)								
300 Homes	--	24.01	--	--	--	45.07	--	--
Unvented Gas Space Heaters								
Palmer 1979 (18)	--	288	--	--	--	--	--	--
Girman, et al. 1982 (7)								
Environmental Chamber	1500	--	6	--	--	--	--	--
CPSC 1933 (9)								
Model	--	1720	--	140.4	--	--	--	--

TABLE 5-1. SELECTED RESULTS DOCUMENTING EFFECTS OF SPECIFIC POLLUTANT SOURCES (CONTINUED)

SAMPLE	MAXIMUM CONCENTRATIONS OBSERVED							
	NO ₂ (ppb)		CO (ppm)		RSP ($\mu\text{g}/\text{m}^3$)		SO ₂ (ppm)	
	PEAK	AVERAGE	PEAK	AVERAGE	PEAK	AVERAGE	PEAK	AVERAGE
Unvented Gas Space Heaters (continued)								
Koonitz, et al. 1988 (19)	--	251	--	5.5	--	--	--	--
157 Homes								
Gas Appliances								
Wade, et al. 1975 (27)	150	100	11.1	6.2	--	--	--	--
Kitchens in 4 Homes								
Holtzwell, et al. 1975 (28)	572	--	38	--	--	--	--	0.028
5 Homes								
Palmer, et al. 1977 (18)	--	58	--	--	--	--	--	--
Homes with Gas Stoves								
Melia, et al. 1978 (25)	--	70	--	--	--	--	--	--
Gas Kitchens								
Florney, et al. 1979 (23)	--	317	--	--	--	--	--	--
428 Gas-Cooking Kitchens								
Spengler, et al. 1979 (15)	--	44.4	--	--	--	--	--	--
Kitchens in 112 Gas Homes								
Brunskreef, et al. 1986 (35)	--	118	--	--	--	--	--	--
Kitchens in 15 Homes								
Wilson, et al. 1986 (36)	--	217	--	--	--	--	--	--
1 Home								
Borrazzo, et al. 1987 (39)	220	--	6.1	--	--	--	--	--
Townhouse 1 Living Room								

TABLE 5-1. SELECTED RESULTS DOCUMENTING EFFECTS OF SPECIFIC POLLUTANT SOURCES (CONTINUED)

SAMPLE	MAXIMUM CONCENTRATIONS OBSERVED							
	NO ₂ (ppb)		CO (ppm)		RSP (µg/m ³)		SO ₂ (ppm)	
	PEAK	AVERAGE	PEAK	AVERAGE	PEAK	AVERAGE	PEAK	AVERAGE
Gas Appliances (continued)								
Attling & Lew 1967 (40)	--	125	--	--	--	--	--	--
Perthurst, et al. 1968 (41)								
Woodburning Stoves, Furnaces, and Fireplaces								
Moschandreas, et al. 1960 (44)	--	--	5.8	--	159.9	57.6	--	--
Traylor, et al. 1962 (8)	227.4	--	8.6	--	--	--	0.064	--
Sexton, et al. 1964 (46)	--	--	--	--	69	25	--	--
Perthurst, et al. 1968 (14)	22.1	--	29.6	18.0	91.4	310	--	--
Tobacco Smoke								
Spangler, et al. 1961, (51)	--	--	--	--	--	120	--	--
Letz, et al. 1963 (54)	--	1	1	75	1	--	--	1

^a Three kerosene heaters operating.

^b Two kerosene heaters operating.

Figure 5-1. U.S. Household Use of Portable Kerosene Heaters, November 1987

Source: U.S. Department of Energy, Housing Characteristics 1987, Report No. DOE/EIA-0314(87), Energy Information Administration, Washington D.C., May 1989.

Figure 5-2. CO, CO₂, NO, and NO₂ Concentrations from Convective Portable Kerosene-fired Space Heaters.

Fuel consumption was 7,830 kJ/hr (7,430 Btu/hr) and the air exchange rate was 0.39 air changes/hr; test #1-1.

Source: Girman, R., et al., Pollutant Emission Rates from Indoor Combustion Appliances and Sidestream Cigarette Smoke, Report No. LBL-12562, Lawrence Berkeley Laboratory, Berkeley, California, May 1982.

Figure 5-3. CO, CO₂, NO, and NO₂ Concentrations from Radiant Portable Kerosene-fired Space Heaters.

Fuel consumption was 8,180 kJ/hr (7,760 Btu/hr) and the air exchange rate was 0.40 air changes/hr; test #3-1.

Source: Girman, R., et al., Pollutant Emission Rates from Indoor Combustion Appliances and Sidestream Cigarette Smoke, Report No. LBL-12562, Lawrence Berkeley Laboratory, Berkeley, California, May 1982.

TABLE 5-2. RANGE OF POLLUTANTS FOUND IN FIELD STUDIES

HEATER TYPE	PIERCE FOUNDATION ^a	WESTON ^b
Radiant	<u>9,600 Btu/hr^c</u>	<u>9,600 Btu/hr^c</u>
NO ₂ , (ppm)	0.07 - 0.15	0.08 - 0.14
CO, (ppm)	3.00 - 19.00 ^d	9.40 - 25.30
SO ₂ , (ppm)	0.07 - 0.22	0.03 - 0.10 ^e
CO ₂ , (%)	0.21 - 0.37	0.39 - 0.75
Convective	<u>8,700-19,500 Btu/hr^c</u>	<u>11,500 Btu/hr^c</u>
NO ₂ , (ppm)	0.08 - 0.31	0.21 - 0.38
CO, (ppm)	0.00 - 3.40	2.60 - 6.20
SO ₂ , (ppm)	0.03 - 0.65	0.07 - 0.10 ^e
CO ₂ , (%)	0.33 - 0.54	0.82 - 1.09 ^e

^a Peak levels measured in 13 homes; Pierce Foundation data was adjusted to the area of the Weston study home.

^b Maximum one hour average measured in one home.

^c Manufacturer's rated output.

^d The 19 ppm value was measured in a closed room with an operating heater.

^e Weston reported 24-hour average exposure. CPSC staff adjusted these values to an average exposure during heater use. This adjustment would result in a value approaching a steady-state level and would tend to over estimate exposure for burning times of up to 2 to 3 hours.

Source: U.S. Consumer Product Safety Commission, Kerosene Heater Briefing Package, Washington, D.C., June 1983.

This consistency between data was not found in the comparison of field-determined decay rates for NO₂ and SO₂ (Table 5-3). Decay rates for NO₂ varied between individual homes by up to seven-fold, while SO₂ decay rates varied by up to 9.5 fold.

As part of its evaluation, CPSC conducted a study to estimate exposure to kerosene heater emissions based on 24 tests performed on 12 individual heaters. The emission rates calculated were used in three models to estimate exposure under steady-state and dynamic concentration conditions. Table 5-4 presents the results of steady-state modeling calculations for a room with door(s) open to the rest of the house. (User surveys indicate that in about 90 percent of the homes surveyed, the heater room was partially or completely opened to the rest of the house). The modeled values agree with field studies data; where discrepancies exist, they are generally within a factor of two. Dynamic and steady-state modeling results were found to be roughly equivalent when based on a typical 6- to 9-hour burn time.

TABLE 5-3. COMPARISON OF FIELD-DETERMINED DECAY RATES

POLLUTANT	DECAY RATES, HR ⁻¹			
	PIERCE FOUNDATION		WESTON	
	RANGE	MEDIAN	RANGE	MEDIAN
NO ₂	0.32-2.32	1.33	0.31-0.54	0.40
SO ₂	0.42-3.99	1.54	0.22-1.18	0.46

Source: U.S. Consumer Product Safety Commission, Kerosene Heater Briefing Package, Washington, D.C., June 1983.

TABLE 5-4. POLLUTANT EXPOSURE LEVELS FROM KEROSENE HEATERS^a

HEATER TYPE	CONCENTRATION RANGE		
	CO, PPM	CO ₂ , %	NO ₂ , PPM
Blue Flame			
6,800 Btu/hr ^b	2.9-8.7	0.15-0.25	0.05-0.1
10,400 Btu/hr ^b	5.1-22.2 ^c	0.23-0.36 ^c	0.09-0.17 ^c
White Flame			
6,800 Btu/hr ^b	1.1-1.8 ^d	0.15-0.24	0.12-0.17 ^c
10,400 Btu/hr ^b	1.2-1.8 ^c	0.23-0.36 ^d	0.11-0.23 ^{c,e}
15,600 Btu/hr ^b	0.8-2.7 ^c	0.34-0.55	0.17-0.37 ^c

^a Based on CPSC steady-state modeling calculations for a room with door(s) open to the rest of the house. Model assumptions were: 0.5 and 0.8 air changes/hr, 0.3 hour reactive decay, 1150 ft² house. Based on user surveys, CPSC staff projects a 5-7 hours exposure to the levels indicated in Table 5-4 during an 8-hour heater use period.

^b Heat outputs were calculated from fuel consumption during operation, at a "normal" setting.

^c Pierce Foundation data for 13 continuously monitored houses fell within these ranges for 9,600 Btu/hr flame heaters and for white flame heaters of 8,700, 13,100, and 19,500 Btu/hr.

^d Based on one heater only.

^e Weston data fell within these ranges for their 9,600 Btu/hr blue flame heater and 11,500 Btu white flame heater.

Source: U.S. Consumer Product Safety Commission, Kerosene Heater Briefing Package, Washington, D.C., June 1983.

Leaderer, et al. conducted a field study of the pollutant exposures associated with the use of kerosene space heaters in over 150 homes (10). Air pollutant levels were analyzed for their association with building characteristics, pollutant sources, and source use patterns. The mix of indoor pollutant sources encountered (e.g., kerosene heaters, gas stoves, and tobacco combustion) allowed an assessment of the impact on indoor air quality of pollutant sources in addition to kerosene heaters.

The two-week average NO_2 and SO_2 levels by location in the residence for the six general source categories are shown in Table 5-5. Residences with one kerosene heater and no gas stove have NO_2 levels four to five times the level of residences without heaters or a gas stove. These levels are roughly comparable to homes with just a gas stove. NO_2 levels above $100 \mu\text{g}/\text{m}^3$ (EPA annual average ambient health standard) were exceeded in approximately 5 percent of the residences with either a gas stove or a kerosene heater, while a much higher portion of the residences with multiple sources exceeded the $100 \mu\text{g}/\text{m}^3$ level. SO_2 levels exceed $80 \mu\text{g}/\text{m}^3$ (EPA annual average ambient health standard) in at least 20 percent of the homes with kerosene space heaters. (The mean sulfur level in 49 fuel samples analyzed was 0.038 percent sulfur, with 45 percent of the samples greater than 0.04 percent K-1 grade kerosene.)

The data in Table 5-5 represent average levels over two weeks and do not reflect the actual exposure levels that existed while the kerosene heaters were being used. To compensate for this, these data were adjusted to reflect actual exposure levels. It was, thus, shown that over 49 percent of the residence had average NO_2 concentrations in excess of $100 \mu\text{g}/\text{m}^3$, with 8.4 percent in excess of $480 \mu\text{g}/\text{m}^3$ (California one-hour ambient health standard). Mean NO_2 levels for the living room and bedroom were $184.3 \mu\text{g}/\text{m}^3$ and $1227 \mu\text{g}/\text{m}^3$ ($n=95$), respectively. Over 71 percent of the residences had average SO_2 concentrations greater than $80 \mu\text{g}/\text{m}^3$, with 21.4 percent in excess of $365 \mu\text{g}/\text{m}^3$ (EPA 24-hour ambient health standard). Mean SO_2 levels for the living room and bedroom were $243.8 \mu\text{g}/\text{m}^3$ and $325.2 \mu\text{g}/\text{m}^3$, respectively.

Consumer and Corporate Affairs Canada funded an in-house study which tested four radiant and four convective kerosene heaters for their impact on CO , CO_2 , and NO_x levels indoors (11). No breakdown of recorded NO_x with respect to relative proportion of NO_2 and other oxides of nitrogen was provided. The test site was a detached, two-story house with three bedrooms on the second floor, with an air exchange rate of 0.2 to 0.3 air changes/hr.

An examination of the data revealed, not unexpectedly, that the highest concentrations of emission products in the bedroom occurred when the door and window were closed. For example, after one hour in the closed bedroom, heaters 1 and 7 generated concentrations of 40.1 and 35.8 ppm CO , respectively, and heaters 11 and 16 produced levels of 3.1 and 5.7 ppm NO_x , respectively. When either the door was opened 50 mm or the window 25 mm, all the gas concentrations were markedly lower and the temperatures marginally lower than those observed when both the door and window were closed. By comparison, after one hour in the bedroom with the window open 25 mm or the door open 50 mm, heater 1 produced levels of 13.9 and 9.3 ppm CO , respectively, and heater 11 generated levels of 1.8 and 1.5 ppm NO_x . Similar decreases in gas concentrations were observed with the other heaters. Opening the door 500 mm permitted the gases to migrate to the other bedrooms, albeit at slightly lower concentrations. However, there was essentially no increase in the concentration of these combustion gases on the ground floor.

TABLE 5-5. TWO-WEEK AVERAGE NO₂ AND SO₂ LEVELS BY LOCATION FOR HOMES IN THE SIX PRINCIPLE SOURCE CATEGORIES

SOURCE CATEGORY LOCATIONS	MEAN NO ₂ , (μg/m ³) ²	PERCENT >100 (μg/m ³)	MEAN SO ₂ , (μg/m ³) ²	PERCENT >80 μg/m ³
<u>No Kerosene Heater or Gas Stove</u>				
Outdoors	13.2	0.0	--	--
House Average	7.4	0.0	0.6	0.0
Kitchen	7.6	0.0	--	--
Living Room	7.3	0.0	1.1	0.0
Bedroom	7.3	0.0	1.7	0.0
<u>One Kerosene Heater, No Gas Stove</u>				
Outdoors	12.9	0.0	--	--
House Average	36.8	2.1	68.4	24.0
Kitchen	39.1	4.2	--	--
Living Room	38.5	5.2	72.4	28.0
Bedroom	31.9	5.3	62.9	20.0
<u>No Kerosene Heater, Gas Stove</u>				
Outdoors	14.8	0.0	--	--
House Average	34.3	4.8	0.5	0.0
Kitchen	44.7	4.8	--	--
Living Room	30.4	4.8	1.1	0.0
Bedroom	27.8	4.8	0.0	0.0
<u>One Kerosene Heater, Gas Stove</u>				
Outdoors	14.5	0.0	--	--
House Average	66.8	16.7	89.9	33.3
Kitchen	74.5	22.2	--	--
Living Room	57.4	11.1	45.6	33.3
Bedroom	68.5	16.7	134.1	33.3
<u>Two Kerosene Heaters, No Gas Stove</u>				
Outdoors	16.5	0.0	--	--
House Average	69.5	23.0	120.4	40.0
Kitchen	73.0	23.0	--	--
Living Room	73.6	--	90.1	60.0
Bedroom	67.8	23.1	150.7	60.0
<u>Two Kerosene Heaters, Gas Stove</u>				
Outdoors	22.1	0.0	--	--
House Average	85.8	33.3	110.0	50.0
Kitchen	94.0	66.6	--	--
Living Room	77.6	33.3	118.0	50.0
Bedroom	85.8	33.3	101.9	50.0

Source: Leaderer, B.P., et al., "A Field Study of Indoor Air Contaminant Levels Associated with Unvented Combustion Sources", presented at the 77th Annual Meeting of the Air Pollution Control Association, June 24-29, 1984.

In considering the data, it was assumed that the upper limit of the comfort range is 82°F (28°C), and that most people would shut off their heater when room temperature exceeded this value. The times at which room temperature reached 82°F (28°C) and the corresponding combustion gas concentrations for each test are given in Table 5-6. The time required to reach 82°F (28°C) was relatively short for the bedroom tests; the maximum time was 35 minutes for heater 6 and the next longest time was 32 minutes for heater 7. By 32 minutes, heater 7 had generated a gas concentration of 9.1 ppm CO but not detectable NO_x. Heater 6, on the other hand, had generated gas levels of 6.0 ppm CO and 1.0 ppm NO_x after 35 minutes, and during the next 90 minutes, the room temperature increased by only 4°C, to 32°C, while the NO_x level remained at 1.0 ppm.

During the living room tests, several heaters did not raise the living room temperature to 82°F (28°C) after three hours of operation in spite of an additional heat source, the gas sampling system. The most notable of these is heater 11 which generated a NO_x level of 0.5 ppm at the end of two hours and 0.9 ppm after three hours. Under these conditions, occupants of the house would have been exposed to NO_x concentrations greater than 0.5 ppm for more than an hour, no matter where they were on the ground and second floors. It was observed qualitatively that the temperatures in the bedrooms were noticeably cooler than the living room. Consequently, it is possible that a temperature above 82°F (28°C) might be tolerated in the living room so that more heat could be transmitted to the other rooms. If such were the case, the time of exposure to NO_x concentrations above 0.5 ppm would be even longer.

Ritchie and Oatman measured the effect of ventilation, heater age, and heater size in relation to room size on indoor pollutant levels in a 1975 townhouse (12). Table 5-7 shows the maximum and average pollutant concentrations based on sampling immediately upon ignition of the heater, during four hours of operation, and one hour after heater shutoff. ASHRAE recommended guidelines were exceeded or approached under several operating conditions.

The rate of buildup of pollutants occurred rapidly within one hour after heater start up. One hour after the heaters were turned off, concentrations of NO, NO₂, and CO₂ decreased by about 40-50 percent, SO₂ decreased by about 75 percent, and CO decreased by about 25 percent. During the ventilation tests, decreases were rapid after the heaters were turned off for all pollutants (70-80 percent), except for CO and NO₂ which decreased at slower rates.

The effect of heater size on pollutant concentrations relative to room size was significant. When the 11,500 Btu heater was operated in the bedroom (164 ft²), concentrations of 0.80 ppm NO, 0.23 ppm NO₂, and 0.86 percent CO₂ were measured after only 1.5 hours of heater operation without ventilation. The heater in this case was 2.5 times larger than required based on floor area of the room. Even when two times the recommended ventilation was provided by opening a window, concentrations were still above ASHRAE standards after two hours. The study concluded that an opening to the outdoors of at least 4 in²/1000 Btu/hr heater capacity is required for proper ventilation, and that recommendations relating heater size to room size should be followed. This study also demonstrated that high concentrations of particulates can result from kerosene heater use. Previous studies employing chamber experiments either did not sample for particulates or observed negligible particulate concentrations. Ritchie and Oatman suggest past findings were probably a result of sampling constraints imposed by the chamber setting.

TABLE 5-6. TEST ROOM GAS LEVELS AT 82°F (28°C)

HEATER NO. AND BRAND	ROOM AND TEST CONDITION ^a	INITIAL ROOM TEMPERATURE, (°F)	TIME TO REACH 82°F (28°C), MIN	NO _x (ppm ^b)	CO (ppm ^b)	CO ₂ (%)	OUTSIDE TEMPERATURE RANGE (°F)
1. Sunbeam CHRG28H	BR: WC/DC BR: WC/DC BR: WO/DC LR	75 70 72 70	5 13 8 --	-- -- -- 0.1	5.5 6.2 6.7 10.2	0.3 0.2 0.3 0.5	61 - 63 52 - 57 45 - 52 39 - 41
6. Kero-Sun Moonlighter	BR: WC/DC BR: WC/DO BR: WO/DC LR	63 64 66 77	23 17 35 --	0.9 0.6 1.0 --	7.0 4.9 6.0 3.2	0.6 0.5 0.6 0.3	37 - 43 43 - 54 37 - 52 41 - 43
7. Kero-Sun Radiant 10	BR: WC/DC BR: WC/DO BR: WO/DC LR	64 57 57 72	12 17 32 173	0.1 0.2 -- --	8.6 9.1 9.1 10.3	0.4 0.6 0.5 0.5	34 - 36 34 - 36 39 - 41 37 - 41
11. Keymar Sundowner KH-80	BR: WC/DC BR: WC/DO BR: WO/DC LR	69 66 66 70	16 6 11 --	0.7 0.6 0.9 0.9	4.9 1.7 1.7 2.5	0.6 0.4 0.5 0.5	48 - 54 50 - 54 48 - 52 37 - 45
13. Kero-Sun Omni 85	BR: WC/DC BR: WC/DO BR: WO/DC LR	79 77 72 77	2 4 7 40	-- -- -- --	0.3 2.7 2.1 --	0.1 0.1 0.3 0.3	54 - 56 59 - 61 43 - 48 46 - 54
14. Kero-Sun Radiant 8	BR: WC/DC BR: WC/DO BR: WO/DC LR	72 75 70 75	8 8 10 40	-- 0.3 0.2 --	7.4 7.7 6.4 2.2	0.4 0.3 0.4 0.2	43 - 48 52 - 54 43 - 45 41 - 54
15. Kero-Sun Radiant 10	BR: WC/DC BR: WC/DO BR: WO/DC LR	64 70 64 73	9 8 12 113	-- -- -- --	6.6 4.4 5.7 3.4	0.6 0.4 0.5 0.5	43 - 45 56 - 57 43 - 52 41 - 54
16. Irwin Turco Heritage	BR: WC/DC BR: WC/DO BR: WO/DC LR	72 72 63 79	2 1 5 16	-- -- 0.3 --	1.1 0.9 1.7 0.4	0.2 0.2 0.4 0.2	36 - 43 34 - 43 34 - 43 54 - 64

^a BR - bedroom; WC - window closed; DC - door closed; DO - door open; WO - window open; LR - living room.^b Corrected for initial background levels - Indicates gas was not detected.

Source: Clarkson, S.B., et al., "Results of Testing Unvented Kerosene Heaters in a House: Gas Emissions, Surface Temperatures and Fuel Consumption Rates," presented at the 77th Annual Meeting of the Air Pollution Control Association, June 24-29, 1984.

TABLE 5-7. POLLUTANT CONCENTRATIONS MEASURED IN A RESIDENCE DURING THE USE OF THREE CONVECTIVE KEROSENE HEATERS OPERATED FOR 4-HOUR PERIODS

	PARTICULATE MATTER ^a ($\mu\text{g}/\text{m}^3$) avg.	SULFUR DIOXIDE (ppm) avg. (max.)	NITRIC OXIDE (ppm) avg. (max.)	NITROGEN DIOXIDE (ppm) avg. (max.)	CARBON MONOXIDE (ppm) avg. (max.)	CARBON DIOXIDE (%) avg. (max.)
11,500 Btu new heater Smaller than required ^b						
Without ventilation 0.49 ach; ^c 65°F start, 81°F end ^d	168	0.141 (0.16)	0.28 (0.34)	0.05 (0.06)	3.1 (4)	0.32 (0.41)
With ventilation ^e 1.1 ach; 64°F start, 76°F end	117	0.112 (0.14)	0.14 (0.2)	0.05 (0.06)	1.8 (2)	0.15 (0.2)
18,000 Btu new heater Larger than required						
Without ventilation 0.81 ach; 63°F start, 82°F end	149	0.183 (0.225)	0.43 (0.58)	0.04 (0.06)	4.5 (5)	0.37 (0.45)
11,000 Btu 5-year old heater Smaller than required						
Without ventilation 0.65 ach; 62°F start, 72°F end	349	0.102 (0.12)	0.21 (0.3)	0.11 (0.13)	6 (7)	0.23 (0.25)
Control-no heater						
Without ventilation 62°F start, 65°F end	39	0.005 (0.005)	0.02 (0.02)	no ² detected	2 (2)	0.05 (0.05)
ASHRAE recommended guidelines for indoor air	260 (24-hr avg.)	0.140 (24-hr avg.)	0.41 (24-hr avg.)	0.05 (annual avg.)	9.0 (8-hr avg.)	0.25 (continuous)

^a Formaldehyde was not detected (LDL of 0.1 ppm) during any of the tests.

^b A heater rated at 13,800 Btu/hour would be required based on the floor area (490 ft²) of the space to be heated; because of a vaulted ceiling, the volume (about 4640 ft³) was larger than for a home with a conventional 8 ft ceiling.

^c CO₂ decay was used to determine ach (air changes/hour).

^d O₂ decreased by 1 percent from 21 percent.

^e Indoor temperatures at start and end of 4-hour tests.

^f Ventilation provided by opening a window; 44 in²/11,000 Btu/hour heater output.

Source: Ritchie, I.R. and L.A. Dattam, "Residential Air Pollution from Kerosene Heaters," *Journal of Air Pollution Control Association*, Vol. 33, September 1983.

Ryan, Spengler, and Letz conducted a two-phase study of kerosene heater emissions which involved monitoring of NO_2 concentrations in a school and two residences and modeling of both SO_2 and NO_2 concentrations and exposures (13). In the first residence, the occupants used two kerosene heaters as the primary heat source. A radiant heater was located in the living room, and a convective heater was located at the opposite end of the house in the kitchen. A wood burning stove located in the basement was effectively sealed off from the rest of the house. This home was a moderately tight house as indicated by both blower door and tracer gas measurements. In the second residence, a single radiant kerosene heater located in the living room was used to supplement the primary heat source: a wood burning stove located in the kitchen. A large fan was placed in the doorway to the kitchen to improve the efficiency of the wood stove by blowing warm air to the remainder of the house. This residence was measured as quite leaky by blower door measurements.

The results from the field study are presented in Table 5-8. NO_2 concentrations were much higher in Residence 1. In this residence, the lack of concentration gradients in the living area, and the lack of exchange between the basement and living area confirms that Residence 1 has a relatively low infiltration rate. The NO_2 levels found in Residence 1 agree quite well with those found in the school monitoring for rooms heated by kerosene heaters. The presence of large concentration gradients in Residence 2 may be attributed to the unusual air flow pattern in the building caused by continuous ventilation from the fan. The authors conclude from the results of the monitoring study that differences between various mean levels are caused by:

- Differences in the use patterns and emission rates of the kerosene heaters
- Differences in air exchange rates
- Unusual airflow patterns caused by forced ventilation.

For the modeling portion of the study, a differential equation was used to describe the rate of change with time of the pollutant concentration indoors. Indoor and outdoor pollutant concentrations, ventilation rate, source emission strengths, and first-order decay constants are all factors. The model assumes instantaneous whole house mixing.

The results of modeling NO_2 concentrations in homes with kerosene heaters for air exchange rates of 0.3, 1.0, and 3.0 air changes/hr are shown in Figure 5-4. Steady-state values, which are reached in 2-8 hours, are quite high, Figure 5-5 shows the levels of SO_2 which may be expected in a well-mixed 350 m^3 house assuming only K-1 kerosene (0.04 percent sulfur) is used. The steady-state concentrations found for all ventilation rates exceed the annual National Ambient Air Quality Standards (NAAQS) of 80 $\mu\text{g}/\text{m}^3$. For $R=0.3$ air changes/hr, steady-state concentrations approach the 24-hour NAAQS of 365 $\mu\text{g}/\text{m}^3$. The authors note that the use of fuels with higher sulfur content than K-1 kerosene, such as No. 1 range oil or No. 2 heating fuel, could result in steady-state concentrations two to three times higher.

TABLE 5-8. NO₂ LEVELS IN TWO VERMONT RESIDENCES, PPM^a

	PERIOD 1 ^b	PERIOD 2 ^c
Residence 1		
Basement	0.01	0.01
Dining room	0.16	0.14
Living	0.16	0.12
Outside	0.002	0.005
Residence 2		
Living room	0.04	0.03
Kitchen	0.01	0.02
Upstairs	0.03	0.03
Outside	0.008	0.01

^a Mean of three diffusion tubes.

^b Basis: 81 hours for residence 1 and 174 hours for residence 2.

^c Approximately 144 hours for both residences.

Source: Ryan, P.B., J.D. Spengler, and R. Letz, "The Effects of Kerosene Heaters on Indoor Pollutant Concentrations: A Monitoring and Modeling Study," Atmospheric Environment, Vol. 17, July 1983.

The State of Maine Office of Energy Resources distributed a press release (24 November 1981) indicating the potential for levels of 2900 $\mu\text{g}/\text{m}^3$ (1/2 ppm) of SO₂ in a moderate-sized energy efficient home after 10 hours of heater operation using No. 1 range oil. Although the use of such fuels is not recommended by the manufacturers, the unavailability of "clean" kerosene or its expense could lead some consumers to other sources of fuel.

As part of the larger Harvard Indoor Air Quality Respiratory Health Study, 300 homes in the Kingston/Harriman region in Tennessee were monitored to study the relationship between wood smoke, kerosene heater emissions, and tobacco smoke on indoor air quality (14,15). In this study, occupant and building questionnaires were used to obtain information on behavioral and physical factors affecting indoor air quality within the homes, and levels of CO₂, RSP, and other pollutants were monitored. Passive samplers were employed.

Using indoor NO₂ and RSP data from the 300-home study, a series of comparisons were made with the three different environmental factors (tobacco smoking, wood heating, and kerosene heaters). A set of 16 2x2 comparisons were formulated, with the results shown in Tables 5-9 and 5-10.

Figure 5-4. Predicted NO₂ from a Kerosene Heater with R=0.3, 1.0, and 3.0 ACH

Source: Ryan, P.B., J.D. Spengler, and R. Letz, "The Effects of Kerosene Heaters on Indoor Pollutant Concentrations: A Monitoring and Modeling Study," Atmospheric Environment, Vol. 17, July 1983.

Figure 5-5. Predicted SO₂ from a Kerosene Heater with R=0.3, 1.0, and 3.0 ACH

Source: Ryan, P.B., J.D. Spengler, and R. Letz, "The Effects of Kerosene Heaters on Indoor Pollutant Concentrations: A Monitoring and Modeling Study," Atmospheric Environment, Vol. 17, July 1983.

TABLE 5-9. DISTRIBUTION OF RESPIRABLE PARTICLES IN CIGARETTE SMOKING, WOOD HEATING, AND KEROSENE ENVIRONMENT, $\mu\text{g}/\text{m}^3$

SEASON	SMOKING	WOOD HEATING		KEROSENE HEATING	
		NO	YES	NO	YES
Winter	No	35.72	29.26	27.24	45.07
	Yes	73.06	72.57	74.72	69.72
Summer	No	26.08	23.69	24.22	26.39
	Yes	51.30	51.52	48.45	56.02

Source: Parkhurst, W.J., "Influence of Indoor Combustion Sources on Indoor Air Quality," Environmental Progress, Vol. 7, November 1988.

TABLE 5-10. DISTRIBUTION OF NITROGEN DIOXIDE LEVELS IN KEROSENE HEATING, WOOD HEATING, AND CIGARETTE SMOKING ENVIRONMENTS, PPB

SEASON	KEROSENE HEATING	WOOD HEATING		SMOKING	
		NO	YES	NO	YES
Winter	No	9.38	5.13	6.19	8.08
	Yes	29.12	16.64	24.01	25.67
Summer	No	7.16	5.57	5.36	7.53
	Yes	6.81	6.36	6.35	6.96

Source: Parkhurst, W.J., "Influence of Indoor Combustion Sources on Indoor Air Quality," Environmental Progress, Vol. 7, November 1988.

It was concluded from the data in Tables 5-9 and 5-10 that kerosene heating in the winter had a clear effect on indoor NO_2 and RSP levels. Homes with kerosene heaters had winter-time NO_2 levels typically 200 percent higher than homes without kerosene heaters, and significant RSP level differences between the two home types were also observed.

It was concluded from this study that the primary effects on indoor air quality are principally associated with unventilated combustion processes such as kerosene heaters. Additionally, it was found that more gas-phase contaminants such as NO_2 are produced from combustion processes which consume liquid hydrocarbons such as kerosene since these processes occur at relatively high temperatures. Finally, it was observed that peak concentrations, though unreported, were several times those of long-term averages and that further studies quantifying peak exposures from indoor combustion should be undertaken.

Traynor, et al. monitored CO , CO_2 , NO , NO_2 , and O_2 concentrations during the operation of two kerosene-fired space heaters (one white-flame convective and one blue-flame radiant) in an unoccupied test house at high (1800 m) elevation (16). The kerosene heaters were operated alternately in the living room and bedroom of the test house, and concurrent concentration measurements were made in the living room, bedroom, kitchen, and the outdoors.

For the case in which the kerosene heater was operated in the bedroom, the heaters were operated for the time required to raise the bedroom temperature 14°F (8°C), and concentration measurements were taken under conditions where the bedroom window and/or the bedroom door was closed. The reported concentration data, showing the resulting increases in the gases monitored, are presented in Table 5-11. A number of important observations were noted in this study, including:

- As expected, CO concentrations were highest when the radiant kerosene heater was used, but NO_2 concentrations were similar for both heater types.
- Opening the window or door of the bedroom slightly (2.5 cm) to increase the ventilation rate during kerosene heater operation did not reduce short-term peak concentrations because the heater operated longer to achieve the same temperature rise.
- Opening the bedroom door, however, did have the effect of lowering peak CO_2 concentrations.
- The NO_2 emission rate from the convective heater was lower at high altitude than previous emission rate measurements conducted near sea level with the same heater.

As a result of these observations, it was concluded that opening a window or door slightly does not necessarily act to reduce peak pollutant concentrations resulting from the use of kerosene heaters, although inter-room transport rates can be high enough to be important in diluting pollutants from kerosene heaters. From the pollutant concentrations measurements taken in this study, it was concluded that under a wide variety of conditions, the operation of a kerosene heater in a bedroom can result in pollutant concentrations close to or exceeding U.S. or state ambient air quality guidelines.

TABLE 5-11. PEAK POLLUTANT CONCENTRATION (LESS BACKGROUND) IN A BEDROOM FROM USING AN UNVENTED KEROSENE-FIRED SPACE HEATER

TEST CONDITION/ HEATER TYPE	COMBUSTION TIME ^a (H)	BEDROOM DECAY RATE ^b (H ⁻¹)	HOUSE AIR EXCHANGE RATE (H ⁻¹)	MEAN OUTDOOR TEMP. (°C)	INITIAL BEDROOM TEMP. °C (°C)	BEDROOM TEMP. INCREASE (°C)	PEAK POLLUTANT CONCENTRATION (LESS BACKGROUND) (ml/m ³) ^d				
							CO	CO ₂	NO	NO ₂	O ₂
Door/window closed											
Convective heater											
Test 1A	0.83	0.43	--	-1.7	12.4	13.5	0.9	7620	4.63	0.19	-10700
Test 1B	0.75	0.45	--	-2.1	12.7	8.7	2.7	5440	2.15	0.57	-6800
Test 1C	0.37	0.35	--	8.5	12.8	8.3	1.1	3460	1.96	0.12	-5500
Test 1D	0.40	0.38	--	2.7	12.4	9.9	0.5	3790	1.99	0.24	-5100
Radiant heater											
Test 2A	0.83	0.39	--	-3.7	12.7	8.7	17.6	4400	0.06	0.37	-6900
Test 2B	0.52	0.50	--	-0.2	11.8	8.4	13.0	3300	0.19	0.52	-4800
Door open 2.5 cm/window closed											
Convective heater											
Test 3A	1.03	--	0.25	-0.0	14.5	8.6	1.2	4860	2.37	0.43	-6500
Radiant heater											
Test 4A	0.93	--	0.27	-2.3	12.8	8.6	11.8	3870	0.13	0.22	-3100
Door open 74 cm/window closed											
Convective heater											
Test 5A	2.22	--	0.35	-5.5	11.6	8.4	0.6	2440	1.54	0.13	-4200
Radiant heater											
Test 6A	2.77	--	0.29	0.9	12.4	8.1	8.9	2670	0.09	0.12	-4500
Door closed/window open 2.5 cm											
Convective heater											
Test 7A	0.77	0.99	--	3.5	12.7	8.4	1.9	4750	2.16	0.60	-6400
Test 7B	0.42	0.89	--	-1.4	10.1	8.6	2.2	2610	1.17	0.31	-3500
Radiant heater											
Test 8A	0.87	1.17	--	-3.7	12.8	8.4	14.6	4120	0.10	0.28	-5800

- ^a Average fuel consumption rates were 7300 ± 1200 kJ/hr for the convective heater and 6400 ± 300 kJ/hr for the radiant heater. Kerosene heat of combustion is 43.5 kJ/g.
^b Represents total exfiltration from bedroom (31 m³) to outside and to rest of house (205 m³) using CO₂ as the tracer.
^c Approximately the same as the initial house temperature.
^d CO₂ indoor background concentrations were significant, ranging from 360 ppm to 990 ppm (mean = 580 ± 190 mL/m³).

Source: Traynor, G.W., et al., "Indoor Air Pollution and Inter-Room Pollutant Transport due to Unvented Kerosene-Fired Space Heaters," Environment International, Vol. 13, pp. 159-166, 1987.

Gas Space Heaters

Some space heating of homes is provided by unvented gas space heaters. This type of heating is most commonly used in rural areas and warm climates, principally in the southern and southwestern states. While emissions from unvented gas space heaters (UVGSHs) have been characterized (see Section 3, Emissions from Combustion Sources), monitoring data are limited.

Girman and co-workers at LBL measured CO, CO₂, NO, and NO₂ concentrations produced by an unvented gas space heater in a 27 m³ environmental chamber without mechanical ventilation (0.5 air changes/hr) (7) (see Figure 5-6). As part of the same study, a variety of heaters were tested to analyze the effect of tuning (i.e., the air/fuel ratio) on emission rates. Using these data, the LBL researchers calculated steady-state pollutant concentrations from specific heaters operating continuously in a 1400 ft² house (1.0 air change/hr) with well-mixed air (Table 5-12). For the well-tuned heaters, NO₂ concentrations are high and formaldehyde concentrations are lower than prescribed standards. For two of these heaters, CO concentrations approach the EPA 8-hour outdoor standard of 9 ppm; CO₂ concentrations are high relative to the ASHRAE standard. In the case of poorly tuned heaters, NO₂ concentrations remain high, formaldehyde concentrations vary from low to high depending on the shutter opening, and CO concentrations are highly variable; they can approach OSHA's 8-hour standard of 50 ppm and exceed EPA's short- and long-term ambient standards.

In general, observed pollutant concentrations from UVGSHs are influenced by the size of the heater, its state of tuning, the length of operation, the volume of the heated space, and the ventilation rate. The potential for CO and formaldehyde concentrations to reach high levels is very dependent on the volume of the heated space and the ventilation rate, as well as the heater-specific factors just mentioned. NO₂ concentrations, however, are high under a variety of operating conditions.

CPSC modeled the emission rates for four UVGSHs which were tested by LBL, to various consumer use scenarios. Table 5-13 presents the projected CO, CO₂, NO, and NO₂ levels resulting from operation of well-tuned and mal-tuned heaters under different ventilation conditions. This analysis was part of a CPSC study which concluded that "UVGSHs appear to present a risk to consumers through the pollutant emissions associated with normal use and reasonable foreseeable misuse. This risk increases with heater size and decreasing ventilation" (17).

Palmer, et al. measured the relationship of indoor NO₂ concentrations to the use of unvented gas appliances (18). NO₂ concentrations were measured for one week in the kitchen, in the room containing a space heater, and in the unheated living spaces of several dwellings in Gainesville, Florida. The heated and unheated living space are designated rooms A and B in the tabulated results, but there is no distinction between rooms A and B in those homes which were centrally heated. Table 5-14 presents indoor NO₂ levels for these groups of residences. The data show that NO₂ concentrations increase significantly with the addition of unvented gas appliances and/or unvented gas space heaters to the residences. Group 5 shows two measurements on one residence in which there was a heater both in the kitchen and in room A. This home had the highest NO₂ concentrations, both in the kitchen and in room A, than any other residence, indicating that the

Figure 5-6. CO, CO₂, NO, and NO₂ Concentrations Produced by a 31,700 kJ/hr (30,000 Btu/hr) Unvented Gas Space Heater

Source: Girman, R., et al., Pollutant Emission Rates from Indoor Combustion Appliances and Sidestream Cigarette Smoke, Report No. LBL-12562, for Lawrence Berkeley Laboratory, Berkeley, California, May 1982.

TABLE 5-12. CALCULATED STEADY-STATE POLLUTANT CONCENTRATIONS FROM SPECIFIC UNVENTED GAS-FIRED SPACE HEATERS OPERATING CONTINUOUSLY IN A 1400 FT² (130 M²) HOUSE (1.0 AIR CHANGES/HR) WITH WELL MIXED AIR

HEATER ^a	CO ^b	CO ₂ ^b	OXYGEN	FORMALDEHYDE ^{b,c}	NO ₂ ^{b,d}
	mg/m ³	ppm	g/m ³	ppm	µg/m ³
		ppm	%	µg/m ³	ppm
Well-tuned					
12A	4.6	4.0	20.7	118	340
16B	8.8	7.7	20.6	21	420
20C	0.9	0.8	20.5	42	360
40B	8.4	7.3	20.2	90	1,200
60C	1.7	1.5	20.2	57	610
Poorly-tuned					
30A ^e	52.0	45.0	20.5	1,400	430
40C ^e	1.1	0.9	20.5	46	520
30A ^f	16.0	14.0	20.4	78	610
60C ^f	4.6	4.1	20.2	43	700

^a Rated fuel consumption in thousands of Btu/hr and manufacturers code, e.g., 40B = 40,000 Btu/hr (42,200 kJ/hr) heater from manufacturer B.

^b Background concentrations assumed to be zero.

^c A reactive decay constant of 0.4/hr was assumed.

^d A reactive decay constant of 1.3/hr was assumed.

^e Fully open shutter.

^f Fully closed shutter.

Source: Girman, R., et al., Pollutant Emission Rates from Indoor Combustion Appliances and Sidestream Cigarette Smoke, Report No. LBL-12562, for Lawrence Berkeley Laboratory, Berkeley, California, May 1982.

TABLE 5-13. PROJECTED POLLUTANT LEVELS FROM UNVENTED GAS SPACE HEATERS UNDER DIFFERENT MODELS^a

POLLUTANT	WELL-TUNED HEATERS			MIL-TUNED HEATERS		
	12A ^b	16B	30C ^c	30A ^{c,d}	30A ^{e,f}	30A ^{g,h}
CO ₂ , %						
closed room	0.40-0.76	0.40-0.75	--	--	--	--
semi-open room	0.25-0.35	0.31-0.49	--	--	--	--
open room	0.14-0.22	0.25-0.31	0.46-0.74	0.46-0.74	0.46-0.74	0.46-0.74
CO, ppm						
closed room	4.0-7.6	23.4-43.6	--	--	--	--
semi-open room	2.5-3.5	18.1-29.5	--	--	--	--
open room	1.4-2.2	14.2-22.7	1.7-2.7	1.5-2.4	5.2-8.4	87.9-140.4
NO, ppm						
closed room	2.75-5.25	2.34-4.42	--	--	--	--
semi-open room	1.76-2.44	1.85-2.90	--	--	--	--
open room	0.97-1.55	1.44-2.39	3.82-6.10	2.85-4.56	8	--
NO ₂ , ppm						
closed room	0.47-0.88	0.98-1.83	--	--	--	--
semi-open room	0.31-0.61	0.80-1.12	--	--	--	--
open room	0.16-0.22	0.59-0.82	0.46-0.63	0.46-0.63	0.56-0.77	1.25-1.72

^a The range of pollutants given in each column refers to the highest and lowest values predicted under up to four model scenarios reflecting different temperature conditions and home heating load assumptions; for the closed room and semi-open room calculations, a different room size is associated with each set of model conditions so that a 70°F heater room temperature is maintained.

^b Calculations for heater 12A were done on the basis of its measured fuel consumption of 9,050 Btu/hr, other heaters rated outputs were closer to their fuel consumption rates.

^c Closed and semi-open room models are not felt to be appropriate for most home uses of a 30,000 Btu/hr heater.

^d With surplus fuel.

^e With surplus fuel and primary air.

^f This heater generated 1.3 ppm of formaldehyde with surplus primary air only; other heaters generated less than 0.1 ppm in field tests.

^g None detectable in LBL test.

Source: Consumer Product Safety Commission, "Unvented Gas Space Heaters: A Preliminary Report, July 1983," presented at U.S. House of Representatives' Committee on Science and Technology Hearings on Indoor Air Quality Research, No. 54, August 23, 1983.

TABLE 5-14. UNVENTED GAS APPLIANCE USE AND INDOOR NO₂ LEVELS

GROUP NO.	RESIDENCE NO.	KITCHEN		ROOM A		ROOM B		RESIDENCE AVERAGE ^a NO ₂ CONC. (ppb)
		UNVENTED GAS APPLIANCE	NO ₂ CONC. (ppb)	UNVENTED GAS APPLIANCE	NO ₂ CONC. (ppb)	UNVENTED GAS APPLIANCE	NO ₂ CONC. (ppb)	
1	3		2		2		1	3
	3		2		3		2	
	9	None	5	None	4	None	3	
	12		5		3		4	
	Room Average ^a		4		3		3	
2	6		52		18		25	34
	8	Stove	58	None	23	None	9	
	11		54		42		23	
	Room Average ^a		55		28		19	
3	7		88		95		14	96
	2	None	--	Heater	96	None	91	
	2 (repeat)		136		161		142	
	Room Average ^a		112		112		65	
4	10		99		174		47	130
	4	Stove	168	Heater	178	None	144	
	5		189		112		58	
	Room Average ^a		152		155		83	
5	1		212		243		180	222
	1 (repeat)	Heater	231	Heater	288	None	175	
	Room Average ^a		222		286		178	

^a The average value for residences in which measurements were repeated was used as a single value in calculating room averages.^b Average of room averages, each room given equal weight.Source: Palmes, E.D., C. Tomczyk, and A.M. March, "Relationship of Indoor NO₂ Concentrations to Use of Unvented Gas Appliances," 1979.

contributions of the two heaters were additive. Even in room B, the concentration is quite high. The results from Group 3 and 4 indicate a pronounced spreading of NO_2 from the heater to the kitchen and to room B. Typical concentrations in room B were half of the value in the kitchen and heated living space. The authors conclude that although the study represents a small sample of home "the differences in NO_2 concentrations are so striking and consistent that the results are meaningful and represent a warning regarding the use of unvented gas space heaters." Note that these data represent steady-state concentrations resulting from continuous operation. Comparison of the results indicates that steady-state concentrations in the Palmes, et al. study must have been at least as high as those reported by LBL.

In a study sponsored by the Gas Research Institute (GRI), Koontz, et al. monitored 157 residences in four Texas cities for CO and NO_2 (19). The objective of the study was to provide the gas industry with data on concentrations of combustion pollutants in residences where unvented gas space heaters were used as primary or secondary heat sources. The homes included in the study were also investigated with respect to unvented gas space heater and gas range use. In some selected homes, air infiltration rates and time-varying pollutant concentrations were measured. Questionnaires and field technician observations were used to collect information on the characteristics of the structures, the appliances used, and the home occupants. The homes which used unvented gas space heaters as the primary heat source were found to average 250 ppb NO_2 , and CO concentrations averaged 5.5 ppm. NO_2 concentrations exceeded 500 ppb in 17 percent of the homes, and CO concentrations exceeded 9 ppm in 12 percent of the homes. The use of gas ranges for supplemental heat, reported in half of these homes, was reported to have made the indoor air quality problem worse.

Among the conclusions reported in the study were the following:

- The primary factor affecting the usage frequency and the indoor NO_2 concentrations in homes with unvented gas space heaters was the difference between the indoor and outdoor temperatures; however, poor tuning and simultaneous use of many indoor gas appliances appeared to exacerbate the problem.
- Use of the gas range for heating was a common practice among homes with unvented gas space heaters as the primary heat source.

The major predictor within and across homes with regard to NO_2 variations was found to be the difference between indoor and outdoor temperatures. Modeling techniques were used to project the annual average NO_2 concentrations in these homes. A summary of the results from this study is presented in Table 5-15.

Gas-fired Cooking Ranges and Ovens

As shown in Figure 5-7, there were 38.7 million and 37.1 million gas-fired ranges and ovens, respectively, in the United States as of November 1987 (6). The Northeast represents a major user of gas ranges and ovens accounting for 51.5

TABLE 5-15. SUMMARY OF DIFFERENCES AMONG PRIMARY, SECONDARY, AND NON-UVGSH HOMES

CHARACTERISTIC	TYPE OF HOME		
	PRIMARY UVGSH	SECONDARY UVGSH	NON- UVGSH
Number of Homes Monitored	82	29	41
Average Volume, ft ³	8,082	8,897	9,695
Average Airtightness, ACH at 50 Pascals ^a	33.4	20.0	24.5
Average Number of UVGSHs	2.3	1.6	--
Average Total UVGSH Capacity, Btu	43,000	19,700	--
Average Percent of Time with UVGSHs in Use	57	45	--
Average Percent of Time with Gas Range in Use	16	10	6
Average NO ₂ Concentration, ppb ^b	251	113	30
Percent of Homes with NO ₂ Concentrations ≥ 500 ppb	17	3	0
Average CO Concentration, ppm ^b	5.5	2.9	2.2
Percent of Homes with CO Concentrations ≥ 9 ppm	12	0	0

^a Based on blower-door tests.

^b Based on time-integrated measurements averaging 5 days in duration for NO₂ and 15 hours for CO.

Source: Koontz, M.D., et al., A Topical Report on a Field Monitoring Study of Homes with Unvented Gas Space Heaters: Volume III - Methodology and Results, Report No. IL-1734, for Gas Research Institute, Chicago, Illinois, May 1988.

RANGES

OVENS

Figure 5-7. U.S. Household Use of Ranges and Ovens, November 1987.

Source: U.S. Department of Energy, Housing Characteristics 1987, Report No. DOE/EIA-0314 (87), Energy Information Administration, Washington, D.C., May 1989.

and 49.5 percent of all households in the region. In contrast, only 33.1 and 31.9 percent of all households in the West used gas-fired ranges and ovens. Overall, gas-fired ranges and ovens are found in 42.7 and 40.9 percent of all U.S. households, respectively.

Of the variety of combustion sources which have been analyzed for their impact on indoor air quality, the influence of gas appliances is the most well documented. Particular attention has been given to the levels of NO_2 resulting from operation of gas stoves. Measurements of peak, weekly, and annual average concentrations have been reported.

Short-term 5-minute to 1-hour NO_2 concentrations can exceed $1000 \mu\text{g}/\text{m}^3$ (0.56 ppm). Concentrations this high are rarely observed in outdoor air. Measurements taken in kitchens during and just after operation of a gas stove have recorded peak NO_2 values as high as $1,800 \mu\text{g}/\text{m}^3$ (1.0 ppm). A number of epidemiological studies have focused on the incidence of respiratory illness in homes with gas versus electric cooking (20,21,22). Florey, et al. reported one-week mean indoor NO_2 concentrations in 428 gas cooking kitchens of $9 \mu\text{g}/\text{m}^3$ to $570 \mu\text{g}/\text{m}^3$ (0.005-0.317 ppm), while levels in 87 electric cooking kitchens ranged from $10.8 \mu\text{g}/\text{m}^3$ to $338 \mu\text{g}/\text{m}^3$ (0.006-0.188 ppm) (23). Palmer, et al. reported one-week integrated averages of $105 \mu\text{g}/\text{m}^3$ in homes with gas stoves (24). Melia, et al. report hourly average NO_2 concentrations of $126 \mu\text{g}/\text{m}^3$ for gas kitchens (25). Most studies show great variation in NO_2 concentrations among homes with gas appliances.

Spengler, et al. monitored NO_2 concentrations inside and outside 137 homes in Portage, Wisconsin over a one-year period (26). More than 10 percent of the 112 gas homes sampled had overall mean kitchen concentrations exceeding the U.S. annual NAAQS of $100 \mu\text{g}/\text{m}^3$. Given that this rural community had relatively low outdoor NO_2 concentrations, this percentage could be higher in most urban and suburban areas of the United States.

In general, CO levels indoors have also been found to rise with the use of gas appliances. Under typical use conditions, emissions from cooking appliances may raise short-term indoor CO concentrations to between 5 and 10 ppm. When a gas stove is used for heating, a common practice among urban poor in northern climates, concentrations of 25 to 50 ppm have been measured.

In 1973-74, Wade and co-workers conducted an indoor/outdoor sampling program for NO , NO_2 , and CO in four homes equipped with gas stoves (27). The pollutant gases were measured simultaneously at three indoor locations and one outdoor location at each site over a two-week period. Table 5-16 presents the principal data from one home included in the study. House No. 3 was a compact two-story apartment with a small unventilated windowless kitchen.

Figure 5-8 is a time history graph of two-hour average NO_2 levels for a typical four-day period in House No. 1, a large (2000 ft^2) suburban split level. This graph shows the rapid response of NO_2 levels to stove use, followed quickly by the response at the other two indoor locations. The oven, in particular, seems to have the greatest influence on the indoor NO_2 concentrations.

Pollutant concentrations in House No. 4 were the highest in any of the houses tested. This house was smaller (1500 ft^2) and tighter than House No. 1.

TABLE 5-16. HOUSE NO. 3: SUMMARY OF AVERAGE NO, NO₂, AND CO CONCENTRATIONS^a

SEASON AND DATA CATEGORY	SAMPLING LOCATION					AVERAGE STOVE USE (MIN/DAY)		
	KITCHEN ABOVE STOVE	KITCHEN-1 m FROM STOVE	LIVING ROOM	BEDROOM	OUTSIDE	OVEN	BURNERS	TOTAL
Spring 1973								
NO ₂ Concentration, µg/m ³	114		75	58	51	0	11	11
NO ₂ Indoor/outdoor ratio	2.23		1.47	1.14				
NO Concentrations, µg/m ³	53		42	34	21	0	11	11
NO Indoor/outdoor ratio	2.52		2.00	1.62				
CO Concentrations, µg/m ³	4310		3210	2680	2230	14	23	37
CO Indoor/outdoor ratio	1.93		1.44	1.20				
Fall 1973 (Second Half)								
NO ₂ Concentrations, µg/m ³	180	140		70	32	25	49	74
NO ₂ Indoor/outdoor ratio	5.62	4.38		2.19				
NO Concentrations, µg/m ³	111	101		64	20	25	49	74
NO Indoor/outdoor ratio	5.55	5.05		3.20				
CO Concentrations, µg/m ³	7130	6620		5500	2500	70	45	115
CO Indoor/outdoor ratio	2.85	2.65		2.20				

^a Average concentrations are based on daily averages for those days in which 12 valid two-hour averages were obtained. Measurements were made during Spring and Fall 1979.

Source: Wade, W.A., et al., "A Study of Indoor Air Quality," Journal of Air Pollution Control Association, Vol. 25, September, 1975.

Figure 5-8. House No. 1: A Time History of NO₂ Concentrations, Two-Hour Averages

Source: Wade, W.A., Cote, and J.E. Yocum, "A Study of Indoor Air Quality," Journal of Air Pollution Control Association, Vol. 25, September, 1975.

Time histories of NO_2 and CO concentrations are presented in Figures 5-9 and 5-10. The 8-hour NAAQS standard for CO ($10,000 \mu\text{g}/\text{m}^3$) was exceeded in the kitchen of this house.

As part of a diffusion experiment in one home, peak concentrations of NO_x and CO were recorded in the kitchen, living room, and bedroom from the time the burners were shut off until the concentrations decayed to their pre-experiment levels. Table 5-17 presents these data. The following were the main conclusions of the study:

- Emissions from gas stoves contribute NO, NO_2 , and CO to the indoor atmosphere of houses where such stoves are used. Kitchen concentrations of these gases responded rapidly to stove use.
- NO and NO_2 were produced in roughly equal amounts in the homes where testing was conducted. Indoor concentrations of these pollutants were invariably higher than those outside.
- Normal stove operations frequently resulted in NO_2 concentrations in the kitchens averaging over $100 \mu\text{g}/\text{m}^3$ for the two-week sampling periods.
- Comparison of sampling carried out in the spring-summer of 1973 and the fall-winter of 1973-1974 showed that in the colder weather, when the house was closed up more often, pollutant concentrations were more uniformly distributed in the various rooms of the house than in the warmer months.
- A diffusion experiment conducted in one of the houses showed that the half-life of NO_2 (0.6 hour) was only one-third that of CO (2.1 hours) and NO (1.8 hours), indicating that NO_2 decays through reaction or adsorption, in addition to normal dilution from air exchange. This effect was observed in some of the other houses by comparing the relative concentrations of NO_2 and the other pollutants in various parts of the house.

Field studies performed by LBL from August 1975 to October 1975 measured air pollutant levels in six homes under typical occupancy conditions of cooking and heating (28). The results indicated high levels of CO, NO, and NO_2 and elevated levels of SO_2 from gas stoves, even during non-cooking periods when pilot lights are probably the only major indoor source of these gases (see Figure 5-11). Figure 5-11 also shows elevated levels of NO and NO_2 resulting from the operation of a forced-air gas-fired furnace system.

One of the homes in the LBL study was equipped with a ventilation fan above the stove and no exhaust duct from the oven to the outdoor air; the other homes were fitted with an oven exhaust duct but no fan. The effect of different ventilation conditions on gaseous air pollutant levels is summarized in Table 5-18. It is obvious that poor ventilation conditions can have a large effect on indoor pollutant levels resulting from gas oven use. The NO_2 levels observed in the six homes all exceed existing short-term standards (see Section 7, Indoor Air Quality Standards).

Figure 5-9. House No. 4: A Time History of NO₂ Concentrations, Two-Hour Averages, Winter 1974

Source: Wade, W.A., Cote, and J.E. Yocum, "A Study of Indoor Air Quality," Journal of Air Pollution Control Association, Vol. 25, September, 1975.

Figure 5-10.

House No. 4: A Time History of CO Concentrations, Two-Hour Averages, Winter 1974

Source:

Wade, W.A., Cote, and J.E. Yocum, "A Study of Indoor Air Quality," Journal of Air Pollution Control Association, Vol. 25, September, 1975.

TABLE 5-17. PEAK CONCENTRATIONS OF OXIDES OF NITROGEN AND CARBON MONOXIDE DURING DIFFUSION EXPERIMENTS AT HOUSE NO. 2

PARAMETER	PEAK CONCENTRATION ($\mu\text{g}/\text{m}^3$)		
	KITCHEN	LIVING ROOM	BEDROOM
NO_2	1,450	900 (62%) ^a	790 (55%) ^a
NO	2,030	1,560 (77%) ^a	1,400 (69%) ^a
CO	12,800	10,400 (81%) ^a	9,300 (73%) ^a

^a Percent of peak value measured in kitchen.

Source: Wade, W.A., et al., "A Study of Indoor Air Quality," Journal of Air Pollution Control Association, Vol. 25, September, 1975.

The National Research Council of Canada tested the effects of air infiltration rate and range hood operation on indoor concentrations resulting from gas stove use (29). An increase in air infiltration rate from about 0.10 to 0.90 air change/hr resulted in a reduction in maximum levels of CO and NO_2 of about 20 percent. With a range hood in operation, maximum CO and NO_2 levels were reduced by about 50 percent at an exhaust rate of 22 liters/sec (0.20 air changes/hr) and to a negligible level at 94 liters/sec (0.85 air changes/hr). Opening the kitchen window resulted in a significant reduction in CO levels and, to a lesser extent, in NO_2 levels.

Traynor, et al. reported that the results of six range hood experiments showed reductions in the effective emission rates of CO, CO_2 , and NO_2 by 60-87 percent with exhaust rates from 42 to 113 liters/sec (30). Macriess and Elkins reported, on the other hand, a reduction in NO_2 levels for the entire house of 40-50 percent with continuous range hood operation from 33 to 113 liters/sec (31). Traynor, et al. also reported that when house air change rate was increased from 0.30 to 0.83 air changes/hr, the peak CO concentration was reduced by only 20 percent (30). Thus, it may be concluded that an operating range hood removing combustion products at the source is more effective in controlling indoor contaminants generated by gas cooking than an increase in overall ventilation rate.

The influence of gas stoves on indoor air quality was one aspect of a study conducted by the Harvard School of Public Health. This study involved indoor and outdoor monitoring of homes in six cities to assess the impact of gas and electric cooking and heating systems on indoor air and the pulmonary health of residents (26).

Figure 5-11.

Gaseous Indoor and Outdoor Air Pollutant Levels Observed at Homes with Varying Cooling and Heating Configurations

Source:

Hollowell, C.D., et al., Combustion Generated Indoor Air Pollution, I. Field Measurements, 8/75-10/75, Report No. LBL-4416, for Lawrence Berkeley Laboratory, Berkeley, California, 1975.

TABLE 5-18. GASEOUS AIR POLLUTANT LEVELS OBSERVED IN HOMES WITH GAS OVENS^a

	HOME IDENTIFICATION NUMBER			
	No. 2	No. 3	No. 5	
Ventilation Conditions	No Duct Fan Off	No Duct Fan On	Duct No Fan	Duct No Fan
CO, mg/m ³	23	6	2	7
NO, µg/m ³	2000	1000	500	150
NO ₂ , µg/m ³	850	320	150	95
SO ₂ , µg/m ³	110	65	<25	<15

^a Measurements in center of kitchen, approximately 1.5 meters above the floor, with the gas oven at 550°F for approximately 20 minutes.

Source: Hollowell, C.D., et al., Combustion Generated Indoor Air Pollution, I. Field Measurements, 8/75-10/75, Report No. LBL-4416, for Lawrence Berkeley Laboratory, Berkeley, California, 1975.

Spengler, et al. reported the results of one year's indoor and outdoor monitoring for SO₂ and NO₂ in six communities with widely varying outdoor levels (26). With regard to SO₂, the six cities provided a wide range of ambient exposures, with community mean values of 52 µg/m³ in Steubenville to 2 µg/m³ in Topeka. Indoor mean levels revealed the same pattern of spread between cities, but at a lower range. Overall, the SO₂ exposure indoors is approximately 50 percent of the outdoor exposure. These reduced indoor SO₂ values may have led to inadequate definition of exposure in previous epidemiological studies. The authors note that health effects associated with ambient SO₂ concentrations may be overestimating the actual levels where effects are occurring. They explain that this presumes that SO₂ may be acting as a surrogate for some other more reactive compound whose indoor/outdoor relationship may be entirely different from SO₂.

The relationship between indoor and outdoor levels of NO₂ was found to be quite different from that for SO₂. In every community, the overall indoor to outdoor NO₂ ratio is less than one for homes with electric stoves and greater than one for homes with gas stoves. In general, for both gas and electric cooking, the variability indoors was greater than outdoor variability. The indoor difference between homes using gas and electricity is greater than the indoor/outdoor difference between homes using the same fuel. In all but one of the cities, the indoor differences between homes with gas stoves was 3 to 7 times larger than the indoor differences between electric homes.

The influence of kitchen ventilation on indoor NO_2 levels was analyzed by looking at the mean indoor/outdoor difference in NO_2 across communities, according to the cooking fuel type and kitchen ventilation used in the home. Figure 5-12 displays the results. A positive value means indoor levels are higher. Note that when kitchen ventilation to the outside is employed, indoor NO_2 levels in homes with gas stoves are lower than ambient levels.

The authors point out that the mean levels reported in this study could be 5 to 10 times lower than the short-term hourly kitchen NO_2 levels produced during cooking. Furthermore, because samplers were placed in the living room, the actual kitchen annual mean values may exceed $100 \mu\text{g}/\text{m}^3$ (0.05 ppm) if one extrapolates from other studies. The authors add that "our continuous NO_2 measurements in a residence with a gas stove demonstrate that levels exceeding $500 \mu\text{g}/\text{m}^3$ (0.25 ppm) and even $1000 \mu\text{g}/\text{m}^3$ (0.50 ppm) can occur during cooking. These high levels can last from minutes to hours" (26).

In a subsequent report as part of the Harvard Six Cities Studies, Spengler, et al. present the results of one year's monitoring for NO_2 inside and outside 25 electric and 112 gas homes in Portage, Wisconsin (32). Week long integrated measurements were made using diffusion tube samplers twice per season for a total of 8-sample-weeks per home. Mean concentrations for each sampling period are presented in Figure 5-13. NO_2 concentrations inside liquid propane- and natural gas-fueled homes increased dramatically during the fall and winter seasons, presumably due to differences in air exchange rates and possibly cooking frequency. NO_2 concentrations also vary spatially, with bedroom levels typically half of kitchen levels in gas cooking homes.

This study found great variation in long-term average NO_2 levels among gas cooking homes. Ten percent of the gas cooking homes had annual mean kitchen NO_2 levels exceeding the annual NAAQS of $100 \mu\text{g}/\text{m}^3$. Because the outdoor air quality in Portage was relatively pristine, the authors state that this percentage would undoubtedly be higher in most urban and suburban areas in the United States. A similar study conducted by Letz and co-workers in Topeka, Kansas confirmed the results of the Portage, Wisconsin study (33). Similar seasonal and spatial variations in NO_2 were observed, and the indoor NO_2 values recorded in homes with gas and electric cooking were virtually identical.

Sexton, et al. used a modeling approach to predict the percentage of gas homes in each of the six cities which would exceed specific annual average NO_2 concentrations (34). (In order to calculate city-specific gamma distributions, the relationship between mean and variance in the five other cities was assumed to be the same as in Portage, Wisconsin. It was then possible to compute gamma distributions scaled by annual average indoor NO_2 values obtained from the model.) Table 5-19 shows that a substantial percentage of homes in each city are predicted to have annual indoor average above $100 \mu\text{g}/\text{m}^3$. In Steubenville, Ohio, the most polluted of the six cities, approximately 23 percent of the gas homes are projected to exceed $100 \mu\text{g}/\text{m}^3$ (0.05 ppm), and 9 percent to exceed $120 \mu\text{g}/\text{m}^3$ (0.067 ppm). The authors noted that depending only on outdoor or even "average" indoor values would lead to the erroneous conclusion that Steubenville's population was not exposed to concentrations above the standard. While the modeling approach used to generate this data needs to be verified through additional monitoring, the results indicate that a significant fraction of homes with gas stoves may violate existing long-term ambient standards for NO_2 in polluted urban areas.

Figure 5-12. Mean Indoor/Outdoor Difference in NO_2 Levels by Cooking Fuel and Kitchen Ventilation, Averaged Across All Indoor/Outdoor Sites (May 1977-April 1978)

Source: Spengler, J.D., et al., "Sulfur Dioxide and Nitrogen Dioxide Levels Inside and Outside Homes and the Implications on Health Effects Research," Environmental Science and Technology, Vol. 13, October 1979.

Figure 5-13. Mean NO₂ Concentrations for Eight Sampling Periods by Location and Type of Cooking Fuel

Source: Spengler, J.D., et al., "Nitrogen Dioxide Inside and Outside 137 Homes and Implications for Ambient Air Quality Standards and Health Effects Research," Environmental Science and Technology, Vol. 17, 1983.

TABLE 5-19. CALCULATED PERCENTAGE OF GAS-COOKING HOMES WHICH EXCEED SPECIFIC ANNUAL AVERAGE NO₂ CONCENTRATIONS

CITY	% GAS HOMES EXCEEDING ANNUAL AVERAGE NO ₂ CONCENTRATION		
	80 $\mu\text{g}/\text{m}^3$	100 $\mu\text{g}/\text{m}^3$	120 $\mu\text{g}/\text{m}^3$
Portage, Wisconsin	12	3	<1
Topeka, Kansas	18	5	1
Kingston-Harriman, Tennessee	20	6	1
St. Louis, Missouri	32	12	4
Watertown, Massachusetts	35	14	4
Steubenville, Ohio	49	23	9

Source: Sexton, K., R. Letz, and J.D. Spengler, "Estimating Human Exposure to Nitrogen Dioxide: An Indoor/Outdoor Modeling Approach," Environmental Research, Vol. 32, pp. 151-166, 1983.

Brunekreef, et al. reported results from a study of 15 Dutch homes in which the indoor NO₂ concentration was measured repeatedly during a one-year period (35). The purpose of the study was to obtain estimates of within-home and between-home variability in residences containing gas-fired appliances. All of the homes studied used natural gas for cooking. In three homes, an unvented gas-fired water heater was present in the kitchen. In another three homes, a vented gas-fired water heater was present in the kitchen. Diffusion tubes were used to measure weekly average concentrations in the kitchen, living room, and bedroom of each home, once every two weeks. Some data from this study are presented in Table 5-20. The researchers concluded from the study results that:

- In all seasons except summer, NO₂ concentrations in all locations within homes did not vary appreciably.
- Between homes, indoor concentrations were systematically different.

In the spring, summer, and winter of 1984-1985, the Southern California Gas Company (SoCalGas) performed the initial Phase I of a three-phase monitoring program to study the causes and effects of indoor NO₂ in homes in its service territory (36). For Phase I, a one-week test was conducted during each of three seasons to determine:

- One-week average kitchen, bedroom, and outside NO₂ concentrations
- Average whole-house air exchange rate (AER)
- Average absolute humidity in the kitchen and bedroom.

TABLE 5-20. INDOOR-OUTDOOR POLLUTANT CONCENTRATIONS IN AND AROUND 15 DUTCH HOMES

TEST PERIOD	PERCENTILE	ONE-WEEK AVERAGE NO ₂ (μg/m ³)		
		KITCHEN	BEDROOM	OUTSIDE ^a
Spring	90th	146	37	80
	Median	73	48	52
	10th	26	21	28
Summer	90th	153	114	120
	Median	89	69	78
	10th	38	31	32
Winter	90th	213	138	164
	Median	101	70	106
	10th	44	31	64

^a For reference, EPA's ambient standard for NO₂ is approximately 100 μg/m³ (annual average).

Source: Brunekreef, B., et al., "Variation of Indoor Nitrogen Dioxide Concentrations Over a One Year Period," Environment International, Vol. 12, pp. 279-282, 1986.

The chosen measurement technique used passive diffusion (Palmer) tube samplers. Participants exposed the diffusion tubes for one week and laboratories analyzed the tubes after exposure.

Homes with a wall furnace in the SoCalGas study recorded wintertime average NO₂ values that were 26 to 41 μg/m³ higher than homes with a forced air furnace when both contained gas ranges. Homes with floor furnaces were found to have wintertime average NO₂ concentrations that were 44 to 61 μg/m³ higher than homes with a forced air furnace when both contained a gas range. Homes with gas ranges and pilots had 17 to 46 μg/m³ higher average NO₂ concentration during the winter than homes with electric ranges. Compared to homes with electric ranges, pilotless gas ranges had an average of 17 μg/m³ higher NO₂ concentration in the kitchen. No significant difference was found in the bedroom, however, between homes with electric ranges and pilotless gas ranges. Homes with gas ranges also had, on average, higher NO₂ levels during the spring and summer. The greatest difference between homes with a gas versus electric range was observed in the kitchen. More generally, it was observed that:

- Indoor NO₂, measured in the bedroom area, was on average lower than outside NO₂, and indoor kitchen NO₂ was on average greater than outside NO₂.

- One-week average indoor NO_2 was proportional to outside NO_2 .
- Indoor NO_2 appeared to vary seasonally with the highest indoor NO_2 concentrations reported in the winter for most homes and appliance types.

In the foregoing study, further investigations were used to draw conclusions regarding the factors leading to elevated NO_2 concentrations in the homes studied. These investigations and analyses were presented in Section 3, Emissions from Combustion Sources. In an effort related to the above study, Colome, et al. presented data from a study in which indoor and outdoor levels of NO_2 in 41 homes were monitored (37,38). The residents of the homes being studied were mailed a packet every four weeks containing NO_2 Palmes tubes that were placed by the resident in the designated sampling location in the kitchen, master bedroom, and outdoors. Tubes were mailed back by the participants and analyzed. An analysis of the collected data concluded that:

- A good indicator of a high indoor NO_2 value is a high indoor concentration during a previous week.
- Any home exhibits considerable variability from week to week in indoor and outdoor NO_2 concentrations; therefore, any single week may not represent a longer time span.
- A case history demonstrates the potential association between the use of some heating systems and elevated indoor concentrations of NO_2 .

Borrazzo, et al. monitored CO, NO, and NO_2 concentrations in a modern, energy-efficient townhouse equipped with a gas-fired range (39). The objective of the study was to develop and verify a model for predicting the concentrations of these pollutants in townhouses. Two different models were tested: a steady-state model, and a model which accounted for the transient nature of emissions from the gas stove. In order to assess the predictive ability of these models, contaminant levels were measured using commercially available electronic equipment.

Recorded and predicted contaminant concentrations reported by Borrazzo, et al. are presented in Table 5-21 for times corresponding to 1 hour and 1.5 hours of burner operation ($t_b = 1 \text{ hr}$ and 1.5 hr). For these time periods of burner operation, it was observed that the model incorporating a transient term [denoted in Table 5-21 as $S(t)$] was a better predictor of CO and NO concentrations than the steady-state model (denoted in Table 5-21 as S_{ss}), while predicted NO_2 concentrations were the same for both models.

Atkins and Law performed a series of NO_2 measurements using passive integrating monitors on three U.K. homes sited in rural, small town, and urban settings (40). The study, which contained measurements from areas of different ambient NO_2 concentrations, was designed to quantify seasonal variations in the indoor-outdoor NO_2 concentration ratio in houses with or without gas cookers (stoves). Three samplers were exposed inside and three outside each home.

TABLE 5-21. COMPARISON OF MEASURED AND PREDICTED PEAK CONCENTRATIONS IN THE LIVING ROOM^a

	t_p - 1.0 hr CONCENTRATIONS (ppm) ^b			t_p - 1.5 hr CONCENTRATIONS (ppm) ^c		
	MEASURED	PREDICTED USING $S(t)$	PREDICTED USING S_{ss}	MEASURED	PREDICTED USING $S(t)$	PREDICTED USING S_{ss}
CO	6.1	4.6	3.8	5.8	6.1	5.4
NO	0.44	0.53	0.56	0.69	0.73	0.76
NO ₂	0.090	0.087	0.087	0.14	0.22	0.22

^a Values are mean values

^b Five experiments

^c Three experiments

Source: Borrazzo, J.E., "Modeling and Monitoring of CO, NO, and NO₂ in a Modern Townhouse," Atmospheric Environment, Vol. 21, pp. 361-368, 1987.

Samplers exposed inside the home were placed in the kitchen, the living room, and the bedroom.

Ambient NO₂ concentrations in the rural area attained an overall average of 11.0 ppb compared to 17.0 ppb in the city. Winter concentrations were higher than summer at all sites (see Tables 5-22 and 5-23). Generally, homes without gas cookers were found to have lower-than-ambient concentrations of NO₂, while homes with gas cookers had NO₂ levels higher than those outside.

Parkhurst, et al. performed NO₂ sampling and indoor NO₂ monitoring inside five Chattanooga, Tennessee public housing developments (41). The objective of the study was to determine the extent of the indoor NO₂ problem in these developments (which all contained gas ranges), identify the significant factors associated with units containing elevated NO₂ levels, and recommend control measures to the occupants of those units.

Passive diffusion samplers were used to collect NO₂ concentration data. Concentration data obtained during this study are presented in Table 5-24. Several factors were cited as possible contributors to high NO₂ concentrations including the following:

- Mechanical malfunctions related to improper operation and venting of gas appliances

TABLE 5-22. AVERAGE TWO-WEEK NO₂ CONCENTRATIONS FOR SAMPLING SITES IN HOMES A, B, AND C, ppb

	HOME	NO. SOURCE	NO. OF MEASURE- MENTS	INDOOR				OUTDOOR			
				KITCHEN	LIVING ROOM	BEDROOM	AVERAGE	SITE-1	SITE-2	SITE-3	AVERAGE
All Data	A	-	32	5.3	5.1	6.0	5.5	10.9	10.9	11.2	11.0
	B	-	35	10.6	8.5	8.1	9.1	17.9	16.6	17.0	17.2
	C	+	24	107	19.5	21.2	49.2	14.8	14.9	14.5	14.7
Winter	A	-	13	5.2	4.9	8.2	6.1	14.1	14.5	14.6	14.4
	B	-	15	10.7	7.8	7.3	8.6	23.2	19.0	22.0	21.4
	C	+	13	125	19.9	19.3	54.7	18.5	18.7	20.1	19.1
Summer	A	-	19	5.4	5.2	3.7	4.8	8.8	8.5	8.8	8.7
	B	-	20	10.5	9.1	3.8	7.8	13.4	14.9	14.7	14.3
	C	+	11	85.5	19.0	25.8	43.4	11.4	10.3	7.8	9.8

Source: Atkins, D.H.F. and D.V. Law, "Indoor-Outdoor Concentration Ratios for Homes with Gas and Electric Cooking," Indoor Air '87: Proceedings of the 4th International Conference on Indoor Air Quality and Climate, Volume 1, pp. 383-389, Institute for Water, Soil, and Air Hygiene, Berlin, 1987.

TABLE 5-23. CHARACTERISTICS OF HOMES A, B, AND C

HOME	GAS COOKING	SITUATION
A	No	Small rural community (population 250) >1 Km from main road and 3 Km from small town (population 5,000).
B	No	Town of 135,000 population. No large industrial sources of NO ₂ but very high traffic density.
C	Yes	Small town (population 16,000). No local industry, high traffic density.

Source: Atkins, D.H.F. and D.V. Law, "Indoor-Outdoor Concentration Ratios for Homes with Gas and Electric Cooking," Indoor Air '87: Proceedings of the 4th International Conference on Indoor Air Quality and Climate, Volume 1, pp. 383-389, Institute for Water, Soil, and Air Hygiene, Berlin, 1987.

TABLE 5-24. DISTRIBUTION OF AVERAGE INDOOR NO₂ CONCENTRATIONS BY DEVELOPMENT

MEAN NO ₂ CONCENTRATION μg/m ³	HOUSING DEVELOPMENT					
	BOONE	McCALLIE	POSS	WHEELER	GREENWOOD	TOTAL
0-50	32	4	6		6	48
50-100		58	22	28	10	118
100-150		20	1	15		36
150-200		3		2		5
200-250		2	1	2		5
250-300						
>300	—	1	—	3	—	4
	32	88	30	50	16	216

Source: Parkhurst, W.J., "Indoor Nitrogen Dioxide in Five Chattanooga, Tennessee Public Housing Developments," presented at the 81st Annual Meeting of APCA, Dallas, Texas, June 19-24, 1988.

- Ventilation problems within the units leading to insufficient air exchange rates
- Use of the stove for space heating.

Lebret, et al. reported a series of real-time experiments conducted to determine the transient concentration peaks of CO and NO₂ in relation to the use of unvented gas appliances (42). The monitoring program was performed with conventional air pollution monitors to measure temperatures and tracer gas, CO, and NO_x concentrations above gas appliances. In twelve homes, successful measurements were carried out over periods of 135 to 273 hours. Tracer gas was emitted at a constant rate in the kitchens, and the resulting tracer gas concentrations were monitored to assess the degree of mixing. Data were plotted versus time of day and analyzed quantitatively.

Concentrations measured during this experiment are presented in Tables 5-25 and 5-26. It was concluded during this study that indoor NO₂ levels frequently exceed recommended standards because of the use of unvented gas space appliances indoors.

Woodburning Stoves, Furnaces, and Fireplaces

Increasing energy costs, consumer concerns about fuel availability, the economic attractiveness of zoned space heating, and the desire for self reliance has brought about an upswing in the use of solid fuels for residential heating. Wood supplied 0.9 quadrillion Btu to the residential sector in 1987. Approximately 23 million households burned wood, with 5 million households relying on the renewable energy resource as the main heating fuel (43).

TABLE 5-25. CO CONCENTRATIONS IN 12 HOMES, mg/m³

LOCATION	MAXIMUM CONCENTRATIONS		OVERALL MEAN CONCENTRATION
	1-MINUTE AVERAGE	1-HOUR AVERAGE	
Kitchen	5-108	3-56	1-4
Living Room	4-28	2-26	1-4
Bedroom	4-48	1-26	<1-4
Outdoors			<1-2

Source: Lebret, E., et al., "Real-Time Concentration Measurements of CO and NO₂ in Twelve Homes," Proceedings of the 4th International Conference on Indoor Air Quality and Climate, Berlin (West), Vol. 1, pp. 435-439, August 17-21, 1987.

TABLE 5-26. NO₂ CONCENTRATIONS IN 12 HOMES, µg/m³

LOCATION	MAXIMUM CONCENTRATIONS			OVERALL MEAN CONCENTRATION
	1-MINUTE AVERAGE	1-HOUR AVERAGE	24-HOUR AVERAGE	
Kitchen	400-3808	230-2055	53-478	36-227
Living Room	195-1007	101-879	49-259	32-142
Bedroom	57-806	48-718	22-100	16-104
Outdoors				25-70

Source: Lebret, E., et al., "Real-Time Concentration Measurements of CO and NO₂ in Twelve Homes," Proceedings of the 4th International Conference on Indoor Air Quality and Climate, Berlin (West), Vol. 1, pp. 435-439, August 17-21, 1987.

Although woodstoves and fireplaces are vented to the outdoor atmosphere, a number of circumstances can increase indoor emissions from these devices: improper installation (e.g., insufficient stack height); cracks or leaks in or poor fitting of stovepipe; stove design (airtight versus non-airtight); poor stove construction; cracks or warps in the firebox; missing or damaged gaskets; inexperienced operation; wet or green fuel; insufficient kindling; negative air pressure indoors; down-drafts; and accidents, as when a log rolls out of the fireplace (see Section 3, Emissions from Combustion Sources).

Field tests were conducted by LBL on woodburning furnaces and woodburning stoves in three occupied houses (8). House A was a 430 m³ earth-sheltered structure with a woodburning furnace in the basement and a woodburning stove in the living room. House B was heated by a woodburning stove in the living room and had an indoor volume of 460 m³. House C, with an indoor living space of 320 m³, was heated by a forced air woodburning furnace in the basement. Table 5-27 provides data on indoor and outdoor CO, NO, NO₂, and SO₂ peak levels during the operation of a woodburning stove or furnace in Houses A, B, and C. In general, the pollutant levels observed in all three houses are below occupational and ambient air quality standards, although NO₂ levels in House C approach current short-term standards and exceed the annual average NAAQS. Comparisons of indoor pollution levels reveal that emissions from woodburning stoves and furnaces vary both in terms of the mix of pollutants emitted and in their total contribution to indoor air pollution.

These inconsistencies are emphasized by the results of a field monitoring study by Moschandreas, et al. (44). Three residences in the Boston metropolitan area were monitored for two weeks at one outdoor and three indoor locations at each site. Residence A contained a woodburning stove, while Residences B and C contained fireplaces. In Residence A, the woodstove was located in the basement, immediately below the sampled living room zone. The fireplaces in Residences B and C were both located in the activity room that was sampled.

Of the gaseous pollutants monitored in this study (i.e., CO, NO_x, ozone, SO₂, methane, and total hydrocarbons), only CO showed a strong association with woodburning indoors; this contradicts the LBL results (8). Figure 5-14 depicts CO concentrations at Residence A on three successive days. The time series represents average hourly indoor and outdoor concentrations. During the hour following successive reloadings and stoking, CO levels rose substantially and then decayed. Indoor CO levels in this all electric residence are comparable to levels generally found in residences with major CO sources, such as gas cooking and heating facilities.

Table 5-28 presents the average and range of TSP and RSP (<3.5 μm) concentrations and the ratio of indoor to outdoor measurements taken in the 3 residences. The indoor 24-hour integrated TSP samples taken in Residences B and C during fireplace use exceed the primary and secondary NAAQS, respectively. The secondary standard is also exceeded by RSP concentrations in Residence B during fireplace use. The relative indoor emission of RSP from fireplaces is illustrated by the magnitude of the indoor/outdoor ratio in Residences B and C. The effect of an active woodstove on indoor TSP concentrations is shown in

TABLE 5-27. INDOOR AND OUTDOOR POLLUTANT PEAKS DURING WOOD-BURNING STOVE/WOOD-BURNING FURNACE OPERATION

POLLUTANT PEAKS ^a																							
APPLIANCE AND HOUSE CODE	AVERAGE AIR EXCHANGE RATE, hr ⁻¹	HOUSE VOLUME m ³	NUMBER OF APPLIANCE USES	CO				NO				NO ₂				SO ₂							
				INDOOR		INDOOR RANGE ppm	OUTDOOR		INDOOR		INDOOR RANGE ppb	OUTDOOR		INDOOR		INDOOR RANGE ppb	OUTDOOR		INDOOR		INDOOR RANGE ppb	OUTDOOR	
				MEAN ppm	MEAN ppm		MEAN ppm	MEAN ppb	MEAN ppb	MEAN ppb		MEAN ppb	MEAN ppb	MEAN ppb	MEAN ppb		MEAN ppb	MEAN ppb	MEAN ppb	MEAN ppb		MEAN ppb	MEAN ppb
Wood Stove																							
A	0.030 ± 0.04 (3) ^b	430	10	0.7 ±0.2	0.4- 1.1	0.3 ±0.3	10.2 ±6.9	3.1- 21.4	4.2 ±0.9	3.0- 5.5	5.5- 36.3	19.3 ±8.5	3.0 ±1.9	7.0 ±5.6									
B ^c	0.008 ± 0.00 (2)	460	7	1.0 ±0.4	0.5- 1.6	0.4 ±0.2	78.1 ±27.8	45.1 114.6	25.4 ±6.0	17.0- 35.7	48.9- 85.7	64.0 ±12.7	22.0 ±6.5	61.9 ±11.1									
Wood Furnace																							
A	0.030 ± 0.04 (3)	430	3	8.6 ±1.7	6.9- 10.3	0.1 ±0.0	28.1 ±4.2	23.9 32.4	3.1 ±1.4	1.8- 4.6	29.0 78.1	48.2 ±26.3	3.4 ±4.6	19.1 ±20.3									
C	0.40 ± 0.13 (4)	320	2	2.6 ±1.8	1.3- 3.9	0.4 ±0.1	136.4 ±125.2	47.9- 224.9	227.4 ±130.0	135.5- 319.3	No Data	No Data	20.8 ±4.9	No Data									

^a Average of living room, bedroom, and kitchen or family room^b Figures in parentheses represent the number of air exchange rate tests conducted.^c Pollutant levels sustained over long periods of time, rather than episodic.

Source: Traynor, G.W., et al., Indoor Air Pollution from Portable Kerosene-Fired Space Heaters, Wood-Burning Stoves, and Wood-Burning Furnaces, Report No. LBL-14027, for Lawrence Berkeley Laboratory, Berkeley, California, March 1982.

Figure 5-14. Carbon Monoxide Concentrations at Residence A on Three Successive Days

Source: Moschandreas, D.T., J. Zabransky, Jr., and H.E. Rector, "The Effects of Woodburning on the Indoor Residential Air Quality," Environment International, Vol. 4, pp. 463-468, 1980.

TABLE 5-28. INDOOR-OUTDOOR TSP AND RSP CONCENTRATION CHARACTERISTICS OF WOODBURNING AND NON-WOODBURNING DAYS, $\mu\text{g}/\text{m}^3$

RESIDENCE	LOCATION	WOODBURNING			NON-WOODBURNING		
		AVERAGE	IN/OUT RATIO	RANGE	AVERAGE	IN/OUT RATIO	RANGE
TSP							
A	In	85.1	1.8	32.5-180.6	28.3	1.0	13.6-42.0
	Out	46.5		10.0-79.5	28.9		10.7-60.2
B	In	267.0	6.1	Only one wood- burning day	81.0	2.1	31.2-137.5
	Out	44.0			38.1		12.3-140.5
C	In	183.6	8.6	Only one wood- burning day	52.8	1.5	24.8-116.2
	Out	21.6			35.3		17.4-57.3

RSP							
A	In	49.0	1.4	14.3-72.5	28.0	1.0	23.9-31.6
	Out	34.2		22.6-57.6	27.4		13.9-53.7
B	In	159.9	5.3	Only one wood- burning day	40.9	2.9	21.7-66.9
	Out	30.3			14.0		7.3-21.8
C	In	67.6	11.3	Only one wood- burning day	18.8	1.1	6.3-39.0
	Out	6.0			17.9		7.7-30.5

Source: Moschandreas, D.T., J. Zabransky, Jr., and H.E. Rector, "The Effects of Woodburning on the Indoor Residential Air Quality," Environment International, Vol. 4, pp. 463-468, 1980.

Figure 5-15. Depending on the magnitude of the woodburning activity, indoor levels may be higher than corresponding outdoor levels by as much as a factor of four. On Day 3, the Secondary TSP NAAQS was exceeded. The impact of this same woodstove on BaP concentrations is presented in Figure 5-16. BaP, a byproduct of wood combustion, is of particular interest because it is a known carcinogen. Indoor BaP concentrations on woodburning days averaged about five times higher than on days when the woodstove was not in use. The significance of elevated BaP during woodburning activity can be interpreted from Table 5-29. An analysis of BaP concentration ranges indoors suggests that there is little or no difference among the residences except when woodburning occurs; outdoor variations were taken into consideration in this analysis (44).

A study conducted by the Oak Ridge National Laboratory for CPSC provides an example of elevated levels of particulates due to improper operation of a wood/coal stove (45). Initial particulate measurements exceeded $400 \mu\text{g}/\text{m}^3$. Soon after monitoring began, the malfunction was corrected. After 1 hour, particulate levels ranged from $50\text{-}100 \mu\text{g}/\text{m}^3$. Most of the particulate concentration was associated with suspended particles in the respirable size range.

Sexton, et al. conducted an indoor/outdoor monitoring study of 24 homes in Waterbury, Vermont to assess the impact of residential wood combustion on indoor respirable particle levels (46). Nineteen homes had woodburning appliances and 5 did not; none of the homes had occupants who were smokers. Of the 19 homes with woodburning appliances, two also had kerosene space heaters.

Outdoor ambient concentrations were uniformly low (mean = $17 \mu\text{g}/\text{m}^3$). Indoor values were significantly higher (mean = $25 \mu\text{g}/\text{m}^3$) and ranged from 6 to $69 \mu\text{g}/\text{m}^3$. Substantial variability in indoor RSP levels was observed among homes within each of the heating fuel categories (i.e., non-wood, wood, and kerosene). RSP concentrations tended to be higher in woodburning, as opposed to non-woodburning residences. However, observed differences were not statistically significant unless one non-wood home, with elevated concentrations of unknown origin, was deleted from the analysis. Indoor values were significantly higher in rooms with kerosene heaters.

A linear regression model incorporating information on air exchange rate, house volume, fuel use, and outdoor levels accounted for only 20 percent of the variance in indoor RSP concentrations. The data presented indicate that although wood and kerosene fuel appliances can contribute to elevated RSP levels in non-smoking homes, other sources, such as cooking, vacuum cleaning, aerosol spray products, pets, and other activities can also be potentially significant emission sources.

A study by LBL illustrates the difference in pollutant emissions due to non-airtight versus airtight stoves (47). Four models of woodburning stoves were tested to determine their contribution to indoor air pollution. Three models were considered airtight, while one, a Franklin type stove with visible gaps in the stoves construction, was not airtight.

All of the woodburning stoves tested emitted at least trace amounts of CO and suspended particles into the indoor environment based on real-time peaks that correspond to starting, stoking and/or reloading times. This result was confirmed by averaged data. In general, the airtight stoves emitted only minor

Figure 5-15. Indoor-Outdoor 24-Hour TSP Concentrations, Residence A

Source: Moschandreas, D.T., J. Zabransky, Jr., and H.E. Rector, "The Effects of Woodburning on the Indoor Residential Air Quality," Environment International, Vol. 4, pp. 463-468, 1980.

Figure 5-16. Indoor-Outdoor 24-Hour BaP Concentrations, Residence A

Source: Moschandreas, D.T., J. Zabransky, Jr., and H.E. Rector, "The Effects of Woodburning on the Indoor Residential Air Quality," Environment International, Vol. 4, pp. 463-468, 1980.

TABLE 5-29. TYPICAL 24-HOUR INDOOR AND OUTDOOR BaP CONCENTRATIONS AT VARIOUS RESIDENCES IN THE BOSTON METROPOLITAN AREA, $\mu\text{g}/\text{m}^3$ ^a

RESIDENCE TYPE	INDOOR BaP		OUTDOOR BaP	
	MEAN	RANGE	MEAN	RANGE
Gas facilities (non-smoking)	0.4	0.1-0.6	0.5	0.1-2.2
Gas facilities (smoking)	0.9	0.4-1.8	0.4	0.1-1.4
Electric facilities (non-smoking)	1.1	0.2-2.8	0.9	0.3-2.2
Electric facilities woodstove no woodburning	1.0	0.3-1.1	0.8	0.7-0.8
Woodburning	4.7	2.3-8.0	1.3	0.2-4.2
U.S. cities with coking ovens (1975) (400 samples)			1.2	0.3-4.7
U.S. rural (1975) (600 samples)			<0.1	<0.1

^a Urban and rural ambient values are provided for comparison.

Source: Moschandreas, D.T., J. Zabransky, Jr., and H.E. Rector, "The Effects of Woodburning on the Indoor Residential Air Quality," Environment International, Vol. 4, pp. 463-468, 1980.

amounts of pollution indoors. The non-airtight stove was a serious pollution source and the very high levels of indoor TSP can be attributed to this stove. During one test, indoor TSP levels reached 820 $\mu\text{g}/\text{m}^3$, BaP levels reached 490 ng/m^3 , and CO levels reached 43 ppm. Five polycyclic aromatic hydrocarbons (PAH) concentrations were also elevated to two orders of magnitude above outdoor levels when the non-airtight stove was used. In general, NO_2 and NO levels were extremely low for all tests while formaldehyde increased slightly when the non-airtight stove was operated. Indoor air concentrations of TSP, BaP, BbF (benzo[b]fluoranthene), BkF (benzo[k]fluoranthene), BghiP (benzo[ghi]perylene), IcdP (indeno[1,2,3-cd]pyrene) were monitored during the separate operation of three different airtight stoves and one non-airtight stove. Monitoring results for these pollutants are presented in Table 5-30.

The results of this study pointed up the importance of stove design in determining whether a given wood stove is an important source indoor pollutants during operation. In general, the operation of wood stoves which were designated as airtight resulted in only small increases in the observed concentrations of these pollutants, while overall the non-airtight stove was concluded to be a moderate to heavy source of the indoor air pollutants monitored. The importance of experience in operating the wood stoves under consideration was also demonstrated, since it was observed that the importance of the non-airtight stove as an indoor pollution source was greatly lessened when "more knowledgeable" operating procedures were used, although this was found to be much less of a factor with the airtight stoves.

Parkhurst, et al. and Knight, et al. conducted an extensive study on the effects of operating woodstoves on indoor RSP, polynuclear aromatic hydrocarbons (PNA), CO, and NO_2 concentrations (14,48). The study involved the sampling and analysis of indoor and outdoor RSP, PNA, CO, and NO_2 levels in an unoccupied (0.4 air changes/hr) test home. The primary objective of the study was to establish the indoor air quality impacts resulting from the operation of three types of wood stoves under varying operating conditions. This wood stove study was part of a multi-year testing program funded jointly by the Tennessee Valley Authority (TVA), Bonneville Power Administration (BPA), and CPSC, and focused on the effects of differing stove designs (non-airtight, airtight, and catalytic airtight) on indoor air quality.

Pollutant concentrations were measured by: semi-continuous electronic monitors for NO_2 and CO; a stacked filter unit for RSP; and gas chromatograph/mass spectrometry-based analytical techniques for PNA. Air exchange rates were monitored continuously using the tracer gas dilution method.

A summary of the concentrations observed during this study is presented in Tables 5-31 and 5-32. Among the conclusions reached were the following:

- Both airtight and catalytic airtight stoves generally operated with similar source strengths.
- The non-airtight (particularly the Franklin freestanding) stoves were found to have significantly higher source strengths than either of the airtight designs when operated with closed stack dampers. Under these circumstances, the non-airtight stoves generated particulate and CO concentrations in excess of NAAQS.

TABLE 5-30. SUMMARY OF INDOOR AND OUTDOOR TSP AND PAH DATA WHILE OPERATING A WOOD-BURNING STOVE INDOORS

stove test	TSP, $\mu\text{g}/\text{m}^3$		BbF, ng/m ³		BkF, ng/m ³		BaP, ng/m ³		BghiP, ng/m ³		IcdP, ng/m ³		(sum PAH)/TSP, ng/ μg ^a		sampling times, h	
	in	out	in	out	in	out	in	out	in	out	in	out	in	out	in	out
airtight																
A-1	71	12	0.56	0.56	0.31	0.21	0.88	0.47	1.1	0.96	1.7	1.3	0.065	0.30	11.2	11.2
A-2 ^b	28	12	3.8	0.52	1.9	0.23	3.5	0.51	3.7	0.59	6.1	1.3	0.69	0.25	19.6	19.6
B-1	38	19	0.71	1.5	0.23	0.76	0.94	1.9	1.7	1.9	1.7	3.0	0.14	0.47	6.6	6.6
B-2	49	31	0.47	1.0	0.20	0.38	0.48	0.83	1.1	1.1	1.8	1.5	0.084	0.15	14.3	14.3
C-1	24	10	0.17	0.8	0.07	0.30	0.34	0.55	0.37	0.92	1.1	1.2	0.085	0.36	18.7	18.7
C-2	34	18	0.30	1.0	0.13	0.44	0.42	1.1	1.3	1.3	1.5	2.0	0.11	0.33	11.4	11.4
C-3	39	7.2	0.73	1.5	0.28	0.63	0.71	1.2	0.92	1.0	1.8	2.0	0.11	0.86	16.0	16.0
nonairtight																
D-1 ^c	650	14	90	0.90	30	0.37	76	0.61	96	0.82	120	1.5	0.63	0.31	1.0	18.2
	470		94		30		41		65		130		0.75		1.0	
	420		69		22		44		60		93		0.69			
D-2 ^c	320	11	27	0.71	11	0.34	29	0.74	23	0.70	39	1.2	0.40	0.34	2.3	20.5
	380		53		23		66		52		84		0.74		1.6	
	d		d		d		d		d		d		d			
D-3 ^c	430	15	16	2.0	7.5	1.2	19	1.7	18	1.7	29	3.9	0.21	0.70	2.3	14.2
	820		420		200		490		450		740		2.8		0.7	
	1500		320		150		370		340		560		1.2			
D-4 ^c	210	27	32	2.8	16	1.4	37	3.1	35	3.7	51	6.0	0.82	0.62	2.0	18.8
	28		1.4		0.67		2.0		2.8		3.9		0.38		12.8	
	100		11		5.4		13		14		20		0.62			
no stove																
bkgd-1	24	16	0.075	0.62	0.059	0.28	0.16	0.68	0.36	0.48	0.45	0.78	0.047	0.18	17.6	17.6
bkgd-2	19	17	0.056	0.20	0.019	0.082	0.044	0.18	0.085	0.14	0.13	0.25	0.018	0.049	22.9	22.9

^aSum PAH = BbF + BkF + BaP + BghiP + IcdP. ^bUsed as a fireplace. ^cThe first two indoor TSP and PAH values reported are from two separate samples taken at two different times during the test; the third number is an estimate of the average concentration over the entire burn period using real-time relative particulate concentration data. ^dInsufficient data to calculate an average value over the entire burn period.

Source: Traynor, G.W., et al., "Indoor Air Pollution due to Emissions from Wood-Burning Stoves," Environmental Science and Technology, Vol. 21, pp. 691-694, July 1987.

TABLE 5-31. COMPARISON OF RESULTS FOR EACH WOOD STOVE

Wood Heater	RSP			PNA			CO			NO _x		ACPH (1/hr)					
	In*	Out*	In/Out	SS* (mg/h)	In	Out	In/Out	SS (mg/h)	In	Out	In/Out						
													(μg/cu.m.)	(ng/cu.m.)	(ppm)	(ppb)	
1985 TVA/BPA Airtight Wood Heaters—All 12-hr Tests																	
1 (AT-CATR)*	Avg	27.3	26.6	1.0	3.6	991	953	1.8	135	0.9	0.5	1.8	6.4	18.0	0.4	0.6	
	St Dev	9.6	3.4		0.9	1034	432		201	0.2	0.2		40	2.1	7.5	0.1	
2 (AT-CATR)	Avg	36.4	37.3	1.0	3.1	412	251	1.6	66	1.0	0.4	2.5	99	8.4	21.2	0.4	0.4
	St Dev	9.0	14.2		0.8	225	183		43	0.3	0.3		28	3.6	8.6	0.1	0.1
3 (AT-CATR)	Avg	28.6	34.3	0.8	2.3	—	—	—	—	0.9	0.6	1.5	55	10.9	27.9	0.4	0.4
	St Dev	10.9	9.8		1.0	—	—		—	0.2	0.2		30	1.5	5.7	0.1	0.1
4 (AT-CATR)	Avg	33.3	24.3	1.4	3.1	1005	516	2.1	118	1.5	0.4	4.0	182	10.6	50.8	0.5	0.4
	St Dev	8.4	9.9		1.1	121	135		24	0.4	0.2		60	3.3	5.2	0.1	0.1
5 (AT-CONVR)*	Avg	37.8	25.4	1.5	3.4	489	372	1.3	43	0.9	0.4	2.3	64	13.2	21.3	0.6	0.3
	St Dev	1.9	7.4		1.6	94	123		26	0.3	0.1		29	2.3	4.6	0.1	0.1
No-Burn*	Avg	18.6	26.4	0.7	0.9	184	444	0.4	0	0.6	0.4	1.4	12	10.1	19.6	0.5	0.2
1985 CPSC Non-Airtight Wood Heaters—All 12-hr Tests																	
3 (NAT-WB)*	Avg	44.1	19.5	2.3	5.5	1952	606	3.2	243	3.0	0.4	7.5	416	14.1	19.5	0.7	0.4
	St Dev	43.5	6.5		6.3	1056	379		106	2.8	0.1		455	10.5	10.4	0.1	0.1
4 (NAT-FF)*	Avg	91.4	33.3	2.8	11.1	1154	414	2.8	143	3.6	0.4	9.0	530	9.8	15.4	0.6	0.5
	St Dev	82.4	18.8		9.5	809	380		90	5.7	0.1		1062	3.9	5.5	0.1	0.1
5 (NAT-LW)*	Avg	70.5	59.9	1.2	6.9	1136	545	2.1	120	2.0	0.5	4.0	210	9.6	14.5	0.7	0.4
	St Dev	11.6	7.6		1.9	467	250		57	1.0	0.1		173	1.6	2.6	0.1	0.03
No-Burn*	Avg	30.0	45.9	0.7	3.1	868	—	—	—	0.8	0.6	1.4	27	22.1	26.5	0.8	0.3
1980 TVA/BPA Airtight Wood Heaters—All 24-hr Tests																	
1 (AT-CONVC)*	Avg	—	—	—	—	—	—	—	—	1.9	0.8	2.4	162	8.6	16.4	0.0	0.4
	St Dev	—	—	—	—	—	—	—	—	0.9	0.3		154	2.3	6.1		0.3
2 (AT-CATR)	Avg	—	—	—	—	—	—	—	—	1.6	1.3	1.2	70	9.2	23.6	0.4	0.4
	St Dev	—	—	—	—	—	—	—	—	0.4	0.4		55	2.8	7.9		0.1
3 (AT-CONVR)	Avg	21.9	18.4	1.2	2.3	—	—	—	—	1.5	0.9	1.7	95	7.0	15.0	0.5	0.4
	St Dev	14.3	8.0		3.0	—	—	—	—	0.7	0.3		36	3.1	8.4		0.1
4 (AT-CATR)	Avg	59.7	20.4	2.9	7.5	—	—	—	—	3.6	0.6	6.0	375	5.6	10.0	0.6	0.4
	St Dev	47.8	7.5		7.2	—	—	—	—	0.6	0.3		143	1.3	5.1		0.03

In/Out—Indoor/outdoor concentrations
 SS—Pollutant source strength
 ACPH—Test home air exchange rate
 AT-CATR—Airtight catalytic radiant heater
 AT-CONVR—Airtight conventional radiant heater
 NAT-WB—Non-airtight wood box heater
 NAT-FF—Non-airtight Franklin type freestanding fireplace heater
 NAT-LW—Non-airtight top loading laundry wood or coal heater
 AT-CONVC—Airtight conventional, circulator heater
 No-Burn—No-burn tests

Source: Parkhurst, W.J.; "Influence of Indoor Combustion Sources on Indoor Air Quality," Environmental Progress, Vol. 7, November 1988.

TABLE 5-32. AMBIENT AIR QUALITY STANDARDS COMPARED WITH OBSERVED INDOOR CONCENTRATIONS FOR AIRTIGHT AND NON-AIRTIGHT WOOD STOVES

POLLUTANT	AVERAGING TIME	NAAQS	STATE OF CALIF.	AIRTIGHT WOOD HEATERS		NO. TIMES EXCEEDING STANDARD	NON-AIRTIGHT WOOD HEATERS	
				OBSERVED MAXIMUM CONC.			OBSERVED MAXIMUM 1984 STUDY	NO. TIMES EXCEEDING STANDARD
				1983 STUDY	1985 STUDY			
CO	1-hr	35 ppm	250 ppb	9.1 ppm (1-hr)	3.0 ppm (1-hr)	0	29.6 ppm (1-hr)	0
	8-hr	9 ppm		5.7 ppm (8-hr)	2.5 ppm (12-hr)	0	18.6 ppm (12-hr)	2
NO ₂	Annual Avg.	50 ppb		12 ppb (24-hr)	16.5 ppb (12-hr)	0	34 ppb (12-hr)	0
	1-hr			19 ppb (1-hr)	20.5 ppb (1-hr)	0	39 ppb (1-hr)	0
TSP	24-hr (Primary)	260 µg/m ³		159 µg/m ³ (24-hr)	92.3 µg/m ³ (12-hr)	0	475 µg/m ³ (12-hr)	3
	24-hr (Secondary)	150 µg/m ³				2		7

Source: Parkhurst, W.J., "Influence of Indoor Combustion Sources on Indoor Air Quality," Environmental Progress, Vol. 7, No. 4, November 1988.

- Peak CO levels were associated with fuel reloadings.
- The non-airtight wood heaters operated with similar source strengths to airtight wood heaters when they were operated under optimum conditions. However, when operated under "worst case" conditions (stack dampers closed), the non-airtight units produced much higher CO concentrations.

A comparison of the NAAQS with observed maximum one-hour pollutant concentrations is presented in Table 5-32. Graphical interpretations of the data for 12-hour average conditions are presented in Figures 5-17 through 5-19.

Tobacco Smoke

The smoking of tobacco indoors contributes directly to the indoor concentration of the various products of tobacco combustion. The smoke generated by the burning of cigarettes and other tobacco products is a complex mixture of chemical compounds existing in a combination of airborne solid (particulate), liquid (aerosol), and gaseous phases. The different chemical compounds which make up tobacco smoke include not only generic products of combustion such as CO, CO₂, water vapor, and particles, but also more exotic compounds such as nicotine, acrolein, acetone, and benzene (49). A more detailed description of the components of tobacco smoke are presented in Section 3, Emissions from Combustion Sources.

Since some 54 million adult Americans (33 percent of the U.S. population) are smokers, it may be inferred that tobacco smoking is a common source of combustion-generated indoor air pollutants in the residential setting (50). For example, of the 75 percent of home occupants responding to a written questionnaire, 70 percent indicated in one survey that at least one smoker was in residence (3).

CO binds to hemoglobin in the blood with 210 times the affinity of oxygen. Thus, low concentrations of CO in the air can result in substantial carboxy-hemoglobin (COHb) concentrations in the blood. The National Research Council (NRC) reviewed a number of studies which examined CO absorption under a variety of locations and smoking conditions (3). A typical COHb content, resulting from the natural production of a small amount of CO by the body, is 0.5-0.7 percent. Table 5-33 documents CO concentrations and increases in COHb resulting from smoke exposure under experimental conditions. Based on this data, NRC concludes that the greatest extent of smoke pollution that would be tolerated produces COHb of approximately 2.5-3 percent in non-smokers after 1-2 hours. Non-smokers would be expected to have slight increases in their COHb content (1-2 percent) from cigarette smoke in the normal work environment and more (2-3 percent) resulting from heavy smoke pollution. There are several problems, however, in the use of CO as a measure of total smoke exposure; other sources of CO must be factored out and the ability of CO to remain in the atmosphere makes it subject to the effects of filtration and ventilation.

Figure 5-17.

Comparison of Respirable Suspended Particulate (RSP) Concentrations for Airtight and Non-Airtight Wood Heaters, $\mu\text{g}/\text{m}^3$

Source:

Knight, C.V., et al., "Summary of Three-Year Study Related to Wood Heater Impact on Indoor Air Quality," presented at the International Conference on Residential Wood Energy, Reno, Nevada, March 4-5, 1986.

Figure 5-18.

Comparison of Total Suspended Particulate (TSP) Concentrations for Airtight and Non-Airtight Wood Heaters

Source:

Knight, C.V., et al., "Summary of Three-Year Study Related to Wood Heater Impact on Indoor Air Quality," presented at the International Conference on Residential Wood Energy, Reno, Nevada, March 4-5, 1986.

Figure 5-19.

Comparison of Carbon Monoxide (CO) Concentrations for Airtight and Non-Airtight Wood Heaters, ppm

Source:

Knight, C.V., et al., "Summary of Three-Year Study Related to Wood Heater Impact on Indoor Air Quality," presented at the International Conference on Residential Wood Energy, Reno, Nevada, March 4-5, 1986.

TABLE 5-33. ABSORPTION OF SMOKE CONSTITUENTS FROM ENVIRONMENTAL EXPOSURE

LOCATION AND DIMENSIONS	VENTILATION	AMOUNT OF TOBACCO BURNED	CONCENTRATION OF CONSTITUENTS	MEASURE ABSORPTION
Room (80 m ³)	6.4 ACH	46 cigarettes and 3 pipefuls	CO, 4.5 ppm; nicotine, 377 mg/m ³	No change in COHb, 0.6%
Room (30.8 m ³)	11.4 ACH	15 cigarettes in 2 hr	--	Non-smokers: COHb, 1.25-1.77%
	None	15 cigarettes in 2 hr	-- COHb, 1.30-	Non-smokers: 2.28%
Isolated community	--	--	CO, 1 ppm	Non-smokers: COHb, 0.68%
Hospital out-patient department	--	Smoking permitted	CO, 2-4 ppm	Non-smokers: COHb, 0.97%
Office building	--	Smoking permitted	CO, 3-8 ppm	Non-smokers: COHb, 1.12%
Room (170 m ³)	None	105 cigarettes	CO, 30 ppm	Smokers: COHb, 7.5%
	1.2 ACH	107 cigarettes	CO, 55 ppm	Smokers: COHb, 5.8%
	2.3 ACH	101 cigarettes	CO, 75 ppm	Smokers: COHb, 1.3%
Room (68.1 m ³)	one	20 cigarettes by machine; additional smoke added to keep smoke constant for 3 hr	CO, 18-26 ppm	Non-smokers: COHb, 0.73-1.63%
Chamber (14.6 m ³)	None	4 cigarettes initially + 1 cigarette per 30 minutes by machine	CO, 24 ppm	Non-smokers: COHb, 0.75-1%

TABLE 5-33. ABSORPTION OF SMOKE CONSTITUENTS FROM ENVIRONMENTAL EXPOSURE
(CONTINUED)

LOCATION AND DIMENSIONS	VENTILATION	AMOUNT OF TOBACCO BURNED	CONCENTRATION OF CONSTITUENTS	MEASURE ABSORPTION
Room (43 m ³)	None	80 cigarettes and 2 cigars per hr	CO, 38 ppm	Smoker: COHb, 9.6%; urinary nicotine, 1,236 ng/ml Non-smokers: COHb, 2.6%; urinary nicotine, 80 ng/ml
Restaurants and offices	--	8-hr workshift	CO, 2.5-15 ppm	No change in COHb, 2.1%
Room (37.5 m ³)	None	126 cigarettes by smokers in 0.2 hr	CO, 30 ppm	Smokers: COHb, 9.1% Non-smokers: COHb, 2.2%
Car, engine off (2.09 m ³)	None	10 cigarettes in 1 hr	CO, 90 ppm	Smokers: COHb, 10% Non-smokers: COHb, 5%
Office building	--	--	CO, 2.7 ppm	Non-smokers: COHb, 0.63-0.82%

^a ACH = air changes/hr.

Source: National Research Council, Indoor Pollutants, National Academy of Sciences, Washington, D.C., 1981.

Bars, restaurants, and other public settings have been the most frequently studied locations in assessments of the indoor air quality impact of tobacco smoking. However, a few studies have measured TSP and RSP concentrations in indoor residential environments to assess the contribution of tobacco smoke. Some of these are reviewed briefly below.

Spengler, et al. conducted extensive indoor and outdoor monitoring for RSP in six cities (51). A wide sample of home characteristics (i.e., location vis-a-vis ambient pollution levels, ventilation, type of heating/cooking fuel, number of smokers, and volume of traffic) was defined. The most striking difference between indoor and outdoor mean respirable particles (MRP) concentrations was associated with cigarette smoke. Figure 5-20 shows mean monthly values for 80 homes across six cities as a function of the number of smokers in the home. In the absence of smoking, indoor and outdoor concentrations are roughly equivalent.

Indoor concentrations of MRP among cities and within cities were found to be significantly different. In a comparison study, a conservation of mass model was derived describing indoor concentrations in terms of outdoor concentrations, infiltration, and indoor sources (52). The measured data from the six cities were analyzed to identify important building characteristics and to quantify their effect. The long-term mean infiltration rate of outdoor particles was found to be 70 percent; this is reduced to 30 percent in fully air-conditioned homes. Cigarette smoke was found to be the dominant indoor source of MRP. The mean impact of smoking a pack of cigarettes inside is to raise MRP levels by approximately $18 \mu\text{g}/\text{m}^3$. In fully air-conditioned buildings, the recirculation of the interior air increases this impact to approximately $42 \mu\text{g}/\text{m}^3$. The model showed good correlation with observed concentrations.

Leaderer, et al. conducted experiments which explored the relationship between ventilation rates and levels of TSP and CO in occupied spaces resulting from sidestream cigarette smoke (53). Results of experiments assessing equilibrium concentrations of CO and TSP for various smoking and ventilation rates under virtually ideal mixing showed that: 1) the 1-hour NAAQS for CO of 35 ppm was never reached, and the 8-hour standard of 9 ppm was exceeded only for those conditions of low ventilation rate and high smoking rate; 2) both the national ambient primary and secondary air quality standards for TSP ($75 \mu\text{g}/\text{m}^3$ and $60 \mu\text{g}/\text{m}^3$) were exceeded even under conditions of low smoking (4 cigarettes/hr) and high ventilation (68 cfm) per person; and 3) the 24-hour TSP standard ($260 \mu\text{g}/\text{m}^3$) was exceeded in many of the smoking/ventilation combinations.

ASHRAE standard 62-81 prescribes a ventilation rate of 35 cfm/occupant for smoking occupancy, based upon odor acceptability. A major finding of the study was that while the ASHRAE standard is sufficient to meet the NAAQS for CO, a four-fold increase in the ASHRAE ventilation standard would be necessary to reduce TSP concentrations to below the national ambient standard. Additional experiments by the authors showed that a 95 percent reduction in TSP levels could be achieved through the use of an electrostatic precipitator, bringing the TSP levels into compliance with NAAQS.

Letz, et al. applied a microenvironment model (at home, school, in transit, etc.) to children's personal exposures to RSP (54). Table 5-34 presents, for children, the means and standard deviations of outdoor RSP concentrations for

Figure 5-20. Monthly Mean Mass Respirable Particulate Concentrations Across All Cities

Source: Spengler, J.D., et al., "Long-Term Measurements of Respirable Sulfates and Particles Inside and Outside Homes," Atmospheric Environment, Vol. 165, pp. 23-30, 1981.

TABLE 5-34. PREDICTED EXPOSURES TO RESPIRABLE PARTICULATES FOR CHILDREN IN SIX CITIES USING A 5-MICROENVIRONMENT MODEL, $\mu\text{g}/\text{m}^3$

CITY	MEAN OUTDOOR CONCENTRATION	MEAN EXPOSURE	PERCENT ^a >75 $\mu\text{g}/\text{m}^3$
Non-Smoke Exposed			
Portage, Wisconsin	11	26	1
Topeka, Kansas	12	26	1
Watertown, Massachusetts	19	30	2
Kingston-Harriman, Tennessee	17	29	2
St. Louis, Missouri	20	30	2
Steubenville, Ohio	41	40	7
Smoke-Exposed			
Portage, Wisconsin	11	56	25
Topeka, Kansas	12	56	26
Watertown, Massachusetts	19	60	28
Kingston-Harriman, Tennessee	17	59	29
St. Louis, Missouri	20	60	29
Steubenville, Ohio	41	70	38

^a Assuming a gamma distribution with the predicted mean and standard deviation

Source: Letz, R., P.B. Ryan, and J.D. Spengler, "Estimated Distributions of Personal Exposure to Respirable Particles," Proceedings of the 3rd Annual National Symposium on Recent Advances in Pollutant Monitoring of Ambient Air and Stationary Sources, Raleigh, North Carolina, May 1983.

each of the six cities, as well as predicted mean exposures and their standard deviations. Exposure estimates are presented separately for children living with smokers and children living with non-smokers. The estimated percentage of children in the six cities having annual average RSP exposures greater than $75 \mu\text{g}/\text{m}^3$ (the NAAQS for TSP) are presented also. A sizeable percentage of the children living in homes with smokers is shown to have exposures above the NAAQS, even in areas with low outdoor RSP concentrations.

A personal monitoring study by Sexton, et al. looked at average personal exposure to RSP as a function of exposure category (at work, in transit, outdoors) and time exposed (55). Cigarette smoke was found to be an important determinant. The mean personal exposure to RSP of persons exposed to tobacco smoke more than 2 hr/day ($50 \mu\text{g}/\text{m}^3$) was 58 percent higher than individuals who were not subjected to any tobacco smoke ($31.7 \mu\text{g}/\text{m}^3$).

Because tobacco smoke consists of a large number of different components, most monitoring studies have necessarily focused on the measurement of only a limited number of indoor air contaminants in order to gauge the overall impact of tobacco smoking on indoor air quality. In a critical review, the National Research Council noted a number of difficulties with this procedure (56):

- The representativeness of the air contaminant measured to the total environmental tobacco smoke in the space is unknown.
- The proxy air contaminant measured may have a variety of other potential sources that were not accounted or controlled for.

In addition, a number of other typical shortcomings were noted with regard to existing monitoring studies:

- Data were not collected on smoking rates or numbers of smokers.
- Important characteristics of the indoor space being investigated, such as infiltration or volume, were not recorded.

In 1986, the Surgeon General of the United States issued a report on the health effects of involuntary smoking (49). In this report, the Surgeon General reviewed the available literature documenting the indoor air quality impacts of smoking indoors. As a result of this review, the following conclusions were noted:

- Environmental tobacco smoke can be a substantial contributor to the level of indoor air pollution concentrations of respirable particles, benzene, acrolein, N-nitrosamine, pyrene, and CO. Environmental tobacco smoke is the only source of nicotine and some N-nitrosamines in the general environment.
- It has been demonstrated that environmental tobacco smoke has resulted in elevated RSP levels in enclosed places.

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Section 6

CONTROL TECHNIQUES

INTRODUCTION

Indoor concentrations of combustion-generated pollutants can be controlled by a combination of three techniques: removing or limiting the emissions from the sources, removing or controlling contaminants in air by processing the air, and by diluting indoor air with less contaminated air, with or without energy recovery (1). Until approximately ten years ago, maintaining acceptable indoor air quality was predominantly accomplished using dilution by ventilation; however, increasing energy costs have lessened the cost effectiveness of this option and other options must often be re-evaluated. These other options include removal, modification, or local ventilation of strong sources of pollutants.

The selection of the control methods or strategy most suitable to address or prevent a specific indoor air pollution problem can be exceedingly complicated. The proper choices for indoor air pollution control often depend heavily on the singular aspects of the particular home in question: the sensitivity of its occupants, the characteristics of the structure, pollutant sources and locations within the home, and the quality of the ambient air. Additional factors which may play a role in selecting appropriate controls are issues related to making the best use of space, the costs and required effectiveness of the controls, the pollutants involved, and many practical considerations of installation, operation, and maintenance. Despite the complexity of the factors which may lead to indoor air pollution problems, a number of general rules may be stated with regard to the control of combustion-generated air pollutants indoors:

- Major sources of combustion-generated pollutants should be vented to the outdoors; this venting should be designed in such a manner as to prevent the re-entry of these pollutants into the structure.
- Proper maintenance of combustion sources should be practiced, especially in homes with low air exchange rates.
- Usage of combustion sources by home occupants should follow the intended purpose of the appliance; i.e., gas stoves and ovens should not be used as space heaters.
- Unvented combustion sources should only be used in well-ventilated areas.
- A balance between the benefits of energy conservation through home tightening and the costs of pollutant control should be maintained.

Table 6-1 lists various combustion-generated-pollutant control strategies and methods, their effect on pollutant levels, and the types of costs associated with each measure (2). Further information on control methods, including equipment manufacturers and costs efficiencies, has been reported by Fisk, et al. and Shurcliff (3,4).

TABLE 6-1. CHARACTERISTICS OF RESIDENTIAL POLLUTION CONTROL METHODS

CONTROL STRATEGY	CONTROL METHOD	EFFECT ON POLLUTANT LEVELS	ASSOCIATED COSTS
Source Removal	Material or Product Substitution	Eliminates pollutants emitted from the source	Costs for installation and operation of substitute
	Restrictions on Source Use, Sales or Activities	Eliminates pollutants in restricted areas from the source	Costs for enforcement
Source Modification	Design or Usage Modifications	Reduces pollutant emissions from the source	Costs for installation and operation of incorporating new design
Air Exchange	Infiltration	Reduces pollutant concentrations provided outdoor concentrations are lower than indoor	Costs for heating and/or cooling increases with increasing infiltration
	Natural Ventilation	Reduces pollutant concentrations provided outdoor concentrations are lower than indoor	Costs for heating and/or cooling increases with increasing ventilation
	Mechanical Ventilation	Reduces pollutant concentrations provided outdoor concentrations are lower than indoor	Costs for installation and operation
	Local Ventilation	Removes pollutants from nearby source before they spread to rest of house	Costs for installation and operation
	Filtration	Removes airborne particles; generally not effective in removing gaseous pollutants	Costs for installation and operation
Air Cleaning	Electrostatic Precipitation	Removes airborne particles; generally not effective in removing gaseous pollutants	Costs for installation and operation
	Ionization	Removes airborne particles; generally not effective in removing gaseous pollutants	Costs for installation and operation
	Absorption	Removes gaseous or vapor pollutants; however, generally not suitable for residential use	
	Adsorption	Removes gaseous pollutants; generally not effective for gases with low molecular weights	

* Not generally available for residential use

Sources: Sandia National Laboratories, Indoor Air Quality Guide for Designers, Builders, and Users of Energy Efficient Residences, Albuquerque, New Mexico, November 1981.

EA Mueller, Baltimore, Maryland

SOURCE REMOVAL

When a specific indoor combustion activity is known to be the leading cause of poor indoor air quality, source removal should be considered, since it may be the most cost effective and easily accomplished control technique available. Pollutant sources can be removed in three ways:

- Simple removal
- Usage restriction
- Product substitution.

Activities such as wood burning and tobacco smoking are examples of combustion sources that may be removed by personal choice of the occupants. Such modifications to occupant lifestyle in the residential setting are highly dependent on individual preferences. In addition, restriction on source use are less effective since they rely on enforcement to ensure compliance or impose unacceptable demands on occupants.

In cases where a pollutant source provides an important function within the home, replacement with non-polluting functional equivalents may be an option. For example, replacement of an unvented kerosene space heater with an electric space heater will eliminate what may be an important source of combustion-generated pollutants within the home. However, removal of pollution sources is a practical control method only when acceptable substitute products are available. Considerations which may make a substitute unacceptable are added costs of purchase or operation, or simply personal preferences. Additionally, these substitute products must not be important pollutant sources themselves.

SOURCE MODIFICATION

If pollutant emissions from an indoor combustion source are causing an indoor air quality problem, then modifications to its installation, design, or use may reduce emissions to an acceptable level. Examples of source modification strategies that can significantly reduce emissions from combustion sources include the following:

- Altering the design or installation of the source
- Performing proper maintenance on the source
- Modifying source usage practices.

These concepts are briefly described below.

Design or Installation Modifications

Design or installation modifications of a combustion appliance can often be used to reduce pollutant emission rates. For example, burner modifications and replacement of standing gas pilot lights with electronic pilots have been suggested for certain gas appliances. Catalytic add-on or other retrofit devices for woodburning appliances has been indicated to be a cost-effective method for

controlling smoke (5). Fail-safe controls which minimize back-drafting from gas-fired water heaters (at a cost of about \$25) have also been suggested (6).

Improved burner design for gas appliances can also reduce pollutant emissions and lower fuel consumption. By lowering the maximum flame temperatures and combustion chamber temperatures, NO_x emissions can be reduced; however, CO levels may increase due to lowered combustion efficiencies. A source should not be modified when it will increase emissions of another pollutant.

Research projects sponsored by the Gas Research Institute (GRI) have been conducted at the American Gas Association (AGA) Laboratory and Thermo Electron to examine design modifications for reduction of emissions from gas ranges (7). AGA has developed a new flame insert that enables gas ranges to burn cleaner (8). The new design reduces fuel use of a burner from about 9,500 Btu/hr to 5,500 or 6,000 Btu/hr and reduces NO_x emissions by about 40 percent; however, CO levels increase somewhat over standard burner emissions. Thermo Electron has designed and field tested an infrared jet burner which has been shown to reduce NO_x , NO_2 , and CO emissions (7).

At the present time, there are few modification options commercially available that permit retrofit modification of combustion sources to reduce pollutant emissions. Owners are generally limited to operation and maintenance strategies according to the guidance/suggestions of the manufacturer to minimize emissions.

Improved Maintenance

Results from a relatively small amount of research indicate that regular maintenance of fuel-consuming appliances can improve the impact of these sources on indoor air quality, especially when such maintenance identifies and addresses major malfunctions such as blocked vents. In a survey conducted in Southern California, malfunctioning gas appliances were found by Colome, et al. to be one of the leading factors associated with the highest measured indoor NO_2 concentrations (9). In addition, the conduct of a systematic appliance tuning and adjustment program resulted in a small but statistically significant improvement in average NO_2 levels in a group of homes containing wall or floor furnaces. In a brief review, Moschandreas also concluded that although the maintenance of combustion sources has not been studied extensively, existing literature suggested that maintenance of indoor sources will prevent substantial increases in indoor air pollution as these sources age, fall out of adjustment, or malfunction (10).

Typical maintenance items that may be overlooked by appliance users are improper tuning of the flame in kerosene and gas appliances, vents which leak or are blocked, ventilation fans which do not operate, or damaged components of the appliance (1).

Usage Modifications

In some cases, improper use of an indoor combustion appliance may lead to an indoor air quality problem. For example, research by Colome, et al. and Parkhurst, et al. indicated that a substantial number of residents in the areas

covered (Southern California and Chattanooga, Tennessee) by the study used their kitchen range or oven as an unvented gas space heater (1,9). Colome, et al. felt that greater reductions in both average and extreme (peak) indoor NO₂ levels could be accomplished by eliminating this practice than by improved maintenance.

AIR EXCHANGE

Air exchange influences indoor air pollutant levels in structures by diluting indoor air with outdoor air. In general, increased air exchange will improve indoor air quality at the cost of increased energy consumption, although the increased costs can be minimized with heat recovery devices. However, air exchange can also introduce outdoor air pollutants into the residence and, therefore, is applicable only when the outdoor air has lower pollutant concentrations or when the outdoor air is cleaned prior to introduction. Air exchange can simultaneously reduce all pollutant levels, provided outdoor concentrations are less than indoor levels.

Air exchange operates through the following mechanisms:

- Infiltration
- Natural ventilation
- Mechanical ventilation
 - local
 - general.

The effective air exchange rate of a home is a complex product of the interaction of these mechanisms with each other and other factors unique to each home, especially structural characteristics. Air exchange rates in homes are also influenced by outdoor temperature and weather conditions.

Infiltration and natural ventilation are the predominant mechanisms for air exchange in most homes, while mechanical ventilation is more important in commercial and institutional buildings, especially the newer types. Although minimum requirements for air exchange in occupied structures have been specified by a number of organizations (see Section 7, Indoor Air Quality Standards), many factors influence indoor pollutant levels. The actual air exchange rate required to maintain acceptable indoor air quality for specific residences may be difficult to determine. Moreover, since most homes rely on air exchange by mechanisms which are not easily measured (infiltration and natural ventilation), the air exchange rate of a particular home may be difficult to assess without expensive techniques.

Infiltration provides generalized dilution of the indoor air. Infiltration is primarily air leakage inward through cracks and interstices, and through ceilings, floors, and walls of a space or structure. The degree of air exchange by infiltration depends on the building construction methods and materials, climate and surrounding terrain, and occupants' lifestyle. These factors were discussed in greater detail in Section 4, Factors Affecting Pollutant Concentrations. Most infiltration occurs through walls, the floor, and the ceiling. Heating systems, windows, doors, fireplaces, and vents are also significant locations of infiltration.

Natural ventilation is the simplest ventilation technique. Air exchange occurs through intentionally made openings such as open windows or doors, or through non-powered ventilators such as chimneys. Natural ventilation dilutes indoor air from small room areas and is best suited for temporary needs, since it imposes an additional heating or cooling load and, therefore, can significantly increase energy consumption. Buildings and residences can be designed to enhance natural ventilation through simple design provisions (11).

Mechanical ventilation occurs when fans produce forced air movement between the indoors and outdoors. Mechanical ventilation can be either localized or generalized, and can provide for a degree of energy recovery from the exhausted air so as to minimize energy losses. Generalized mechanical ventilation is not commonly provided for in homes, since most home designers rely on natural ventilation and infiltration to provide make-up air.

The following methods are used to provide mechanical ventilation to residences:

- Air-to-air exchangers
- Mechanical exhaust ventilation
- Evaporative coolers.

Residential air-to-air heat exchangers may be simple ductless units installed through a wall or window much like a window air conditioner or may consist of a fan assembly with duct-work installed in an attic or crawl-space (see Figure 6-1). Air-to-air heat exchangers conserve otherwise lost energy by using warm air which is being vented to warm outdoor replacement air in the winter, and using the cool air which is being vented to cool outdoor replacement air in the summer. The larger the temperature difference between inside and outside air, the more efficient the heat exchangers are. Heat-recovery efficiencies of up to 85 percent make them attractive for energy-conservation; however, fan power consumption is highly variable and can reduce energy savings in some cases (12,13).

A typical air-to-air heat exchanger of the size suitable for residential use costs between \$365 and \$475, provides a constant ventilation rate of 70 cubic feet per minute (cfm), and consumes 45 to 55 watts of continuous electric power (14). The more expensive heat exchangers are provided with additional features required for operation in cold climates (typically 5°F and lower). Installation costs for these units are additional and depend on installation design.

The exchangers' intake and exhaust ducts may be only a few feet apart, or may be 10 or 20 feet apart. The farther apart, the less chance there is that some of the exhaust air will find its way back to the intake duct. If there is some nearby outdoor source of pollution, the intake duct should be located as far from the source as possible. It may be advantageous to have the intake duct on the upwind side and exhaust duct on the downwind side of the residence (4).

Experimental studies have demonstrated the effectiveness of air-to-air heat exchangers in reducing indoor pollutant levels. Offermann, et al. measured concentrations of radon, formaldehyde, and particles in houses with and without

1. Supply air intake
2. Heat exchanger
3. Supply air distribution duct
4. Exhaust air inlets
5. Exhaust air vent

Figure 6-1. Design, Window Installation, and Whole house Installation of Air-to-Air Heat Exchangers

Source: Fisk, W.J., et al., Indoor Air Quality Control Techniques: Radon, Formaldehyde, Combustion Products, Noyes Data Corporation, Park Ridge, New Jersey, 1987.

ventilation, using air-to-air heat exchangers (15). Using mechanical ventilation, the average increase in air exchange rate was from 0.35 air changes/hr (ACH) to 0.63 ACH, and radon concentrations decreased by 50 percent, formaldehyde by 18 percent, and particles by 30 percent.

Mechanical exhaust ventilation utilizes a fan to exhaust indoor air, thereby drawing outdoor air into the house through cracks. If the exhaust air is passed through a heat pump, the energy that would otherwise be lost can be recovered. Exhaust-air heat-pump systems are popular in Sweden but are not currently used in the United States (16).

Evaporative coolers provide mechanical ventilation while cooling and humidifying the air. Outside air is forced through a water-saturated filter. The water absorbs heat from the air and evaporates. Evaporative coolers are effective only in warm, dry climates because of the evaporative process (2).

The cost effectiveness of mechanical ventilation systems is an important consideration. Fisk and Turiel evaluated the energy savings that accrued from operating air-to-air heat exchangers in new homes and performed a cost-benefit analysis (17). They found cost effectiveness to be highly dependent upon equipment performance, climate, and type of heating fuel used.

Local ventilation controls pollutant levels by using forced ventilation near a known source to exhaust pollutants to the outdoor atmosphere. Local ventilation is useful with localized sources that operate intermittently. A problem with the use of spot-ventilation exhaust fans in airtight houses is that too much powered exhaust can reduce the natural draft in a furnace vent and can cause combustion products from the furnace to be drawn into the living space (18).

Local ventilation is an important air quality control technique designed into many homes, and should be used in conjunction with the operation of most indoor combustion sources of pollutants. In general, local ventilation increases the effective air exchange rate with less of the energy penalty associated with more generalized increases in air exchange. It is a well established air pollution control technique; an extensive treatment of this subject as it is currently practiced was recently published by ASHRAE (19).

Kitchens or kitchen stoves usually have some form of vented or unvented local exhaust system. Unvented range hoods with charcoal filters can be effective for grease, odors, and other large molecules but not for CO and other small molecules. Filters are somewhat expensive and in normal practice are not changed often enough to be reliable. Therefore, the unvented range hood cannot be considered a reliable pollution control device (18). The performance of vented range hoods depends somewhat on air flow rates, usage patterns, and methods of installation; however, if used, they are generally quite effective in reducing pollutant levels indoors if occupants use them when cooking (20). This has also been established in studies such as those conducted by Traynor, et al. in which reductions of 60-87 percent in CO, CO₂, and NO_x levels were demonstrated through the use of a range hood fan during gas stove operation (21).

AIR CLEANING

Air cleaning operates by removing contaminants after they have been introduced to the living space without added ventilation. An effective air cleaning system can reduce outdoor air requirements in a home and, thus, provide both cooling and heating cost savings. In cases where the outdoor air is of poor quality, air cleaners may be required for occupant health and/or comfort. Moreover, most building codes require at least a minimal amount of air cleaning.

Air cleaners that may be suitable for controlling indoor pollutant levels include the following:

- Mechanical filtration
- Electrostatic precipitation
- Ionization
- Absorption
- Adsorption.

Mechanical filters, electrostatic precipitators (sometimes known as electronic air cleaners), and, to a lesser extent, air ionizers are perhaps the most widely used residential air cleaners. Absorptive and adsorptive air cleaners are designed to remove gaseous or vaporous air contaminants, and are most commonly used in larger commercial or institutional buildings.

There is no single air cleaner capable of controlling particulate, vaporous, and gaseous contaminants. Filters and electrostatic precipitators are used to remove airborne particles; however, they are not effective in removing gases or vapors. Sorption devices can be used for removal of both gaseous and vaporous contaminants, but these devices generally do not control particulates and are not usually cost effective for residential applications. If both particles and gases or vapors are to be removed, air cleaners first must remove the particles and then the gases or vapors (18).

Air-cleaning devices have not been widely used in residences because the devices are expensive to buy and operate, and can be bulky and noisy. However, they are most effective as a component of the heating, ventilation, and air-conditioning (HVAC) system. The location of air-cleaning equipment in a ventilation system will depend on the type of system and its application. The HVAC system schematic shown in Figure 6-2 identifies potential air-cleaning equipment locations. If the concentrations of contaminants in outdoor air are unacceptable, the outdoor air must be cleaned, and recirculated air from living spaces must be cleaned to achieve the same quality as specified for the outdoor air. Special ventilation systems, such as fume hoods, may use air cleaners in the supply and exhaust airstreams (18). Portable air cleaning devices are available, but these are generally effective only in small spaces.

More specific descriptions of the various air cleaning technologies are presented below. A detailed treatment of these technologies was recently compiled by Meckler and Janssen (22).

Figure 6-2. Heating, Ventilation, and Air Conditioning Schematic Showing Possible Air-Cleaner Locations. (Adapted From ANSI/ASHRAE 62-1981)

Source:

American National Standards Institute, and American Society of Heating, Refrigerating and Air-Conditioning Engineers, ANSI/ASHRAE Standard 62-1981: Ventilation for Acceptable Indoor Air Quality, American Society of Heating, Refrigerating and Air Conditioning Engineers, Inc., Atlanta, Georgia, 1981.

Mechanical Filtration

Mechanical filtration is perhaps the most commonly used residential air pollution control method, since simple mechanical filters are supplied with most residential forced-air circulation systems. In many homes, however, the effectiveness of these filters is low because they are not maintained properly. In other cases, homeowners elect to augment their effectiveness by installing electronic air cleaners or other devices to augment the standard HVAC filters.

Air filtration is a method designed to remove particles by passing air through a filter. However, filters are generally not effective in removing gaseous contaminants. Airborne particles are commonly removed by mechanical filter units using one or a combination of the following mechanisms (18):

- Inertial impingement (impaction)--An abrupt change in direction of the airstream causes airborne particles to collide with the filter fiber. This method of collection is most effective with larger particles.
- Interception--This method of collection is a special case of impingement in which a particle collides with a fiber, independent of inertia. This method may be more effective than impingement at low velocities.
- Straining--Airborne particles are captured as they attempt to pass between two adjacent fibers.
- Diffusion--Very small airborne particles are driven to the filter fiber by random molecular bombardment by air molecules. This method is most effective for the smallest particles.

Filters are characterized by their particle removal efficiency, capacity, and resistance to air flow. Removal efficiency may be expressed as a function of the size (mass, physical, or aerodynamic) or number of particles removed. In addition, the air flow rate at which the efficiencies are determined and the air pressure drops imposed by the filter when it is clean and fully loaded are characteristics necessary to evaluate the filter performance. Typical characteristics of mechanical filters are presented in Table 6-2.

Mechanical filters vary widely in their ability to remove particulates from the air. Filters used to remove the largest and heaviest particles are evaluated by weight efficiency and are usually rated as low-efficiency filters. They are used as upstream pre-filters or to protect mechanical devices, such as fans and heat exchangers. These types are commonly used in residential furnaces and central air-conditioning systems. When smaller particles, such as tobacco smoke, must be removed, medium-efficiency filters may be used. However, they are more expensive than low-efficiency filters. Moreover, particle filtration has been reported to be unsuitable for removing irritation and odor from tobacco smoke, since these symptoms have been ascribed to the gaseous phase of the smoke (23,24). High-efficiency particle (HEPA) filters can remove small as well as large particles; however, they are expensive and are generally not used for residential applications.

TABLE 6-2. TYPICAL CHARACTERISTICS OF MECHANICAL FILTERS^a

TYPE OF AIR CLEANER	CONTROL MECHANISM	PRESSURE DROP, ^b Pa	EFFICIENCY			DUST HOLDING CAPACITY g/1,700 m ³ /hr
			WEIGHT ^c	SIZE ^d	NUMBER ^e	
Viscous-impingement filter	Impingement	<125	20-50 50-75 60-80 70-85	5-10 5-15 5-20 10-25	-- -- -- --	70-140 120-560 180-540 240-760
Dry-type extended surface: Open-cell foams Cellulose glass-fiber mats Multiple glass-fiber mats 5-10 m fibers, 6-12 mm thick 3-5 m fibers, 6-20 mm thick 1-4 m fibers and asbestos 0.5-2 m glass fibers 0.1-1 m fibers (HEPA filters)	Impingement and interception	12-250	70-80 80-90 85-90 90-95 >95 >95 -- --	15-30 20-35 25-40 40-60 60-80 80-90 90-98 --	-- -- 5-10 15-20 35-40 50-55 75-90 99.97- 99.999	180-425 90-180 90-180 270-540 180-450 180-360 90-270 500-1,000

^a Adapted from ASHRAE

^b Pressure drop at air velocity of 1-4 m/sec through media; filter-face velocity usually higher.

^c Also described as dust arrestance in ASHRAE Standard 52-76.

^d Also described as atmospheric dust spot efficiency in ASHRAE Standard 52-76.

^e Particle-removed efficiency of 0.3 m (i.e., DOP method), as described in Mil. Standard 282.

^f As described in ASHRAE Standard 52-76.

Source: National Research Council, Indoor Pollutants, National Academy Press, Washington, D.C., 1981.

Some filters are disposable and others can be cleaned and reused. To determine if filtration is an appropriate choice for pollutant control, consideration should be given to trade-offs that exist between filter cost, collection efficiency, capacity, and air flow resistance.

Electrostatic Precipitators

Electrostatic precipitators (ESPs) are used to remove airborne particles by providing an electric charge on the particle, establishing an electric field, and then removing the particle from the precipitator. Electrostatic precipitators can be very effective in removing even submicron particles; however, they are generally not effective in removing gaseous pollutants (24). In addition, they must have filters or collecting plates which must be replaced or cleaned every few months (2).

Electrostatic precipitators designed for residential use are available in a limited number of sizes and are tailored to the cubic-feet-per-minute (cfm) rating of the HVAC system. For example, one major ESP manufacturer offers two sizes of residential ESPs: a 1400 cfm model at approximately \$300 and a 2000 cfm model at approximately \$380 (25). Installation costs are additional.

Electrostatic precipitators commonly used for control of particulate matter in residences include the following:

- Ionizing-plate type
- Charged-media, non-ionizing type
- Charged-media, ionizing type.

Table 6-3 presents performance data for the various types of electronic air cleaners.

TABLE 6-3. RELATIVE PERFORMANCE OF ELECTRONIC AIR-CLEANERS BY TYPE^a

TYPE OF CLEANER	DUST SPOT METHOD	DOP METHOD	PRESSURE DROP, Pa ^b	RELATIVE SPACE REQUIREMENT
Ionizing plate	85-90	65-80	25-40	Maximal
Charged media, non-ionizing	25-35	10-20	40-75	Minimal
Charged media, ionizing	40-60	25-35	40-75	Moderate

^a Values reported are approximate and were obtained from C. W. Soltis, Filterlab, Inc., Houston, Texas

^b At face velocities of 1.5-2.5 m/sec; 1 pascal (Pa) = 1 newton/m²

Source: National Research Council, Indoor Pollutants, National Academy Press, Washington, D.C., 1981.

The performance of electrostatic precipitators commonly used in residences compares favorably with medium and high-efficiency filters and is usually rated in terms of dust spot efficiency. Their major advantage is the low resistance to air flow compared with filters; however, this can be a disadvantage if they are not installed so that there is uniform air velocity at the inlet. When selecting an electrostatic precipitator, compromises are often required with respect to removal efficiency, pressure drop, and space limitations. There is a potential hazard associated with the high voltage at the ionizing electrode, collection plates, and charged media. In addition, ozone can be produced by the high voltage, and soiling of surfaces in the home can be caused by charged dust particles that escape the collection surfaces of the cleaner (18). Many units are equipped with replaceable charcoal filters to remove any ozone which may be generated by the electrical field.

Ionization

Air ionizers control particle levels by producing negative ions which convey negative electrical charges to particles. Particles then attach to walls, floors, and other surfaces. Some models have positive-charged collectors to attract and capture most particles. Although they can be somewhat effective in removing particles from the indoor air, the performance and usefulness of ionizers may be less than indicated in some advertising claims (12).

Some research has been performed on the ability of air ionizers to remove indoor pollutants other than particulates. For example, Repace, et al. investigated the efficiency of negative ion generators for removing ambient tobacco aerosol from typical indoor spaces, since the particulate phase of tobacco smoke is a respirable aerosol difficult to remove by standard techniques (26). Three models of ionizers were tested in three different unventilated rooms polluted to levels of tobacco typical of those found under normal conditions. In every case, the ionizers accelerated the deposition rate of the particulate phase on the room surfaces by factors ranging from 3 to 18. However, it was noted that ionizers may be ineffective in removing gas-phase pollutants from indoor combustion, and should not be considered as substitutes for ventilation or source control. In addition, soiling of room surfaces may be an undesirable attribute in many applications. There is a trade-off between accomplishing a high rate of air cleaning and maintaining a biologically acceptable level of ions. Nevertheless, Repace, et al. concluded that ionizers may be useful adjuncts to primary ventilation systems under conditions where smoking cannot be prevented (26).

Absorption

Absorptive air cleaning works by the penetration of molecules of a given pollutant into a solid or liquid sorbent material. Absorption processes are generally used for gas or vapor removal for industrial applications and are seldom used in residential buildings.

Only air pollutants that are soluble or chemically reactive to the sorbent can be removed by passing the airstream over or through a bed impregnated with absorbent material. For example, absorption by water appears promising for removing formaldehyde and tobacco smoke aerosols (12,27). NO_2 is removed by processes in industry that are complex and generally not suitable for residential

use when NO₂ concentrations are much lower. Absorption of NO₂ into water may be possible if additives to the water are used; however, at this time, this appears impractical for residential use (12).

Removal of gaseous and vapor-phase contaminants may eventually be practical for residential air pollution control equipment. Novosel, et al. are developing an absorbent (desiccant)-based air-conditioner for GRI (28). The objective of the project is to develop a desiccant-based air-conditioner to actively control humidity and many indoor air contaminants.

Adsorption

Adsorption controls pollutant levels by physical or chemical fixation on surfaces or by being trapped in the pores of solid surfaces. Gases having high molecular weights are generally adsorbed easier than gases having low molecular weights. Therefore, removal of CO, NO_x, and formaldehyde by adsorption is difficult by this method. The effectiveness of adsorbents in removing NO₂ from indoor air is unknown, although some studies have demonstrated significant reductions in formaldehyde levels using adsorption (12).

The most commonly used adsorbents are activated carbon, activated alumina, silica gel, and molecular sieves. Adsorbents become saturated after a period of use and must be regenerated or replaced.

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Section 7

INDOOR AIR QUALITY STANDARDS

Currently, there are no regulations that require owners of private residences to monitor or otherwise control indoor air pollution; consequently, there are no mandatory standards for the residential air environment. However, a number of recommended standards do exist that can be used as guidelines for homeowners, home designers, and others concerned about residential indoor air quality. These standards can be categorized into two basic types: health standards (which specify maximum recommended pollutant concentrations) and ventilation standards. These standards are briefly described below.

HEALTH STANDARDS

A summary of the standards and guidelines applicable to combustion-generated air pollutants is presented in Table 7-1. At the present time, health standards have been formulated for outdoor and occupational air quality only, while guidelines have been issued by various organizations with regard to indoor air quality in residences. Health standards have traditionally been developed by occupational safety organizations/institutions [such as Occupational Safety and Health Administration (OSHA) and National Institute of Occupational Safety and Health (NIOSH)] to regulate workplace exposures, and by federal and state agencies (such as EPA) for regulating outdoor air pollution (National Ambient Air Quality Standards) (1,2). In general, permissible pollutant levels allowed by occupational standards are higher than the guidelines set for either outdoor or residential air quality. In recent years, the World Health Organization, the Canadian Department of National Health and Welfare, and other organizations have become active in developing these guidelines for the home environment (1,3). Residential air quality guidelines are relatively new and generally recommend the lowest pollutant levels.

In general, outdoor and occupational air quality standards provide for the absolute maximum concentrations permissible at any particular point in time (peak levels) as well as maximum average concentrations over varying periods of time. This is necessary since these standards regulate the maximum time-averaged dose of pollutants to which individuals are exposed, and the total dose is a function of both time and concentration of the pollutant. Therefore, depending on the scope of the standard, a number of maximum pollutant levels may be specified which correspond to either instantaneous measurements or measurements taken over various average times.

Occupational health standards formulated for use in assessing the hazards of workplace exposures have been developed by NIOSH, OSHA, and the American Conference of Governmental Industrial Hygienists (ACGIH). The OSHA sets standards called Permissible Exposure Limits (PELs) based on the criterion that "no worker will suffer material impairment of health or functional capacity even if such employee has regular exposure to the hazard dealt with by such standard for the period of his/her working life." The NIOSH sets guidelines for maximum pollutant levels known as Recommended Exposure Limits (RELs), which include other guidelines dealing with sampling protocols and worker notification procedures. The ACGIH develops guidelines known as Threshold Limit Values (TLVs), developed under the criteria that "a small percentage of workers may experience discomfort" under conditions at or below the TLV and that "a smaller percentage may be

TABLE 7-1. SAMPLE AIR QUALITY STANDARDS AND GUIDELINES (CONTINUED)

SUBSTANCE	AVERAGING TIME	STANDARD OR GUIDELINE ^{a,b}						COMMENTS	
		PUBLIC HEALTH GUIDELINES		OCCUPATIONAL LIMITS					
		EPA/NAAGS	WHO	ASHRAE	CANADA	OSHA ^c	NIOSH ^d		ACGIH ^e
Nitrogen oxides	Annual		150u						
	24 hr								
	8 hr								
	1 hr								
	30 min								
Particulates (PM-10)	15 min		400u						
	Annual	50u							
	24 hr	150u							
	8 hr								
	1 hr								
Particulates (PM-2.5)	30 min								
	15 min								
	Long term								
	Annual					40u			
	24 hr								
Particulates (TSP)	8 hr								
	1 hr								
	30 min								
	15 min								
	Annual	75u							
Polynuclear aromatic hydrocarbons (carcinogenic fraction)	24 hr	260u							
	8 hr								
	1 hr								
	30 min								
	15 min								

TABLE 7-1. SAMPLE AIR QUALITY STANDARDS AND GUIDELINES (CONTINUED)

SUBSTANCE	AVERAGING TIME	STANDARD OR GUIDELINE ^{a,b}						COMMENTS
		PUBLIC HEALTH GUIDELINES			OCCUPATIONAL LIMITS			
		EPA/NAQS	WHO ^c	ASHRAE ^d	CANADA	OSHA ^e	NIOSH ^f	
Sulfur dioxide	Long term							
	Annual	80u		0u				
	24 hr	365u		65u				
	10 hr						1,300u	5,000u
	8 hr							
	1 hr		350u			13,000u		
	30 min							10,000u
Water vapor (relative humidity)	15 min		500u					
	10 min							
	5 min				1,000u			
				20-60%	30-80% summer 30-55% winter			

^a u = µg/m³; U = µg/m³.

^b Reported values were converted where necessary so that all values for the same chemical are in the same units to facilitate comparisons.

^c World Health Organization Indoor/Outdoor Guidelines.

^d American Society of Heating, Refrigerating and Air Conditioning Engineers, Inc., Indoor Guidelines.

^e Occupational Safety and Health Administration Occupational Standards.

^f National Institute for Occupational Safety and Health Occupational Standards.

^g American Conference of Government Industrial Hygienists Occupational Standards.

^h WHO does not establish guidelines for these substances; instead, the agency publishes risk factors for each substance to indicate potential human health risks per unit of exposure.

Source:

Eisinger, D.S., et al., "New Policy Challenges, Limited Analytical Tools: Using Existing Air Quality Health Standards to Diagnose Indoor Air Quality Problems," presented at the Association for Public Policy Analysis and Management Tenth Annual Research Conference, Seattle, Washington, October 27, 1988.

affected more seriously by aggravation of pre-existing conditions or by development of an occupational illness."

It is important to note that occupational standards have been developed for healthy, working-age adults. It has been suggested that concentrations of contaminants to which the general population is exposed should not exceed 1/10 of occupational standards, since public exposure may be more than 40 hr/week, and because the more susceptible segments of the population (i.e., children and elderly) should be protected (4).

VENTILATION AND DESIGN STANDARDS

Ventilation standards are intended to assure adequate indoor air quality during the design phase of buildings by specifying minimum ventilation rates and standard design practices. Model building codes and standards have been developed by professional organizations and governmental agencies for adoption by local, state, and federal agencies to protect the health and welfare of occupants. Organizations such as the American Society of Heating, Refrigeration, and Air-conditioning Engineers (ASHRAE) and the International Energy Agency (IEA) have put forth standards on ventilation rates (5).

In general, ASHRAE specifies standards which are subsequently incorporated into many building codes. ASHRAE's first ventilation standard, Standard 62-1973, was written just before the oil embargo of 1973 (6,7). In the formulation of this standard, the comfort of occupants was the main concern and the energy penalty associated with excess ventilation was largely ignored. When energy conservation in buildings subsequently became an issue, ASHRAE developed Standard 90-1975 which, in both its 1975 and 1980 versions, provided guidance in building energy conservation techniques and recommended the use of ventilation rates specified in Standard 62-1973 (8). Since the rates specified in Standard 62-1973 were recognized as not conducive to energy conservation, a revision of that standard was undertaken in 1978, with a primary goal of providing increased energy conservation. This revision was completed in 1981 and the standard is designated as Standard 62-1981.

Standard 62-1981 is the most current standard developed by ASHRAE with regard to indoor air quality. This standard attempts to balance the two concerns of acceptable indoor air quality and efficient energy utilization through two separate approaches: specifying minimum ventilation rates for buildings, and outlining procedures for determining the acceptability of indoor air. Minimum ventilation rates specified by ASHRAE Standard 62-1981 are presented in Table 7-2. Although these ventilation rates apply to both buildings and residences, it is difficult to apply these standards to residences due to the problems encountered in measuring the infiltration and natural ventilation rates which are significant in homes. For this reason, assuring indoor air quality in residences using Standard 62-1981 commonly requires the use of the alternative procedure provided therein, namely that of measuring the acceptability of indoor air quality.

ASHRAE Standard 62-1981 defines acceptable indoor air quality as "air in which there are no known contaminants at harmful concentrations and with which a substantial majority (usually 80 percent) of the people exposed do not express dissatisfaction." ASHRAE Standard 62-1981 uses the EPA's National Ambient Air Quality Standards (NAAQS) and other health standards to define the concentrations

TABLE 7-2. OUTDOOR AIR REQUIREMENTS FOR VENTILATING RESIDENTIAL FACILITIES^{a,b}

APPLICATION	OUTDOOR AIR REQUIREMENTS	COMMENTS
General living areas, cfm/room	10	
Bedrooms, cfm/room	10	
All other rooms, cfm/room	10	Ventilation rate is independent of room size
Kitchens, cfm/room	100	
Baths and toilets, cfm/room	50	
Garages ^c , cfm/car space	100	Installed capacity for intermittent use
Garages ^d , cfm/ft ³ floor	1.5	

^a As specified by ASHRAE Standard 62-1981 for private dwelling places, single or multiple, low or high rise.

^b Operable windows or mechanical ventilation systems shall be provided for use when occupancy is greater than usual conditions or when unusual contaminant levels are generated within the space.

^c Separate for each dwelling unit.

^d Common for several units.

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

Janssen, J.E., et al., "Updating ASHRAE Standard 62-1981: Problems and Issues," presented at the APCA Specialty Conference on Indoor Air Quality in Cold Climates: Hazards and Abatement Measures, Ottawa, Ontario, April 1985.

of pollutants which are acceptable. For contaminants that are not thereby referenced in the standard, ASHRAE recommends that their levels should not exceed 1/10 of the occupational standards used in industry. In the case of some mucous membrane irritants, ASHRAE specifies that the air can be considered to be free of annoying contaminants if at least 20 untrained observers, after exposure for no more than 15 seconds, deem the air to be not objectionable under representative conditions of use and occupancy (1).

Since its publication in 1981, a number of problems have combined to limit the acceptance of ASHRAE Standard 62-1981. These problems include:

- The standard has been found to be confusing in certain provisions regarding the purity of outdoor air to be used for ventilation.
- The calculations for the recommended separate ventilation rates for non-smoking and smoking areas have proven to be confusing and difficult in practice.
- The maximum levels for some pollutants provided for in the standard as an alternative to minimum ventilation rates have proved to be controversial.

As a result, ASHRAE Standard 62-1981R, Ventilation for Indoor Air Quality, is currently being formulated to correct the perceived defects in ASHRAE Standard 62-1981. A number of specific revisions are currently being considered, including the following (9,10):

- The portion of the standard dealing with the quality of outdoor air has been restructured to improve clarity.
- The minimum ventilation rate has been raised from 5 cubic feet/minute (cfm) per person to 15 cfm/person in all living areas.
- The designation of certain areas as "smoking permitted" or "smoking prohibited" to calculate design ventilation rates has been abandoned. Only those applications, such as schools, churches, auditoriums, etc. where smoking is prohibited will recommend lower ventilation rates. In these applications, however, the minimum of 5 cfm/person for non-residential structures will probably be raised to 7 to 10 cfm/person for purposes of odor control.
- Although a given building may meet the ventilation rates required by the standard, the indoor air in the building may still be unacceptable due to short-circuiting of the airflows in the supply/return ductwork and factors related to occupancy patterns. Appropriate suggestions and recommendations will be included in the revised standard to alert the engineer/designer about these problems.
- The recommendation of the use of filters for tobacco smoke control will be tempered.
- New measures to reduce the possibility of microbial contamination will be described.
- Information will be presented in a form designed to facilitate the objective of discovering new opportunities for new techniques for air quality control. The major contaminants and their effects at certain levels will be presented.

Recommended ventilation rates specified under the currently proposed Standard 62-1981R are presented in Table 7-3.

To date, ASHRAE Standard 62-1981R has been undergoing internal review and approval, which has been prolonged due to the controversial nature of some of the issues involved, notably tobacco smoke control. Barring further public review which might be necessitated by the appeals process, a final, approved standard is not expected until early 1990 (11).

TABLE 7-3. PROPOSED OUTDOOR AIR REQUIREMENTS FOR VENTILATING RESIDENTIAL FACILITIES^a

APPLICATION	OUTDOOR AIR REQUIREMENTS	COMMENTS
Living Areas	0.35 air changes per hr but not less than 15 cfm/person	For calculating the air changes per hour, the volume of the dwelling shall include all areas within the conditioned space. The ventilation is normally satisfied by infiltration and natural ventilation. Dwellings with tight enclosures may require supplementary ventilation supply for fuel burning appliances, including fireplaces and mechanically exhausted appliances. Occupant loading shall be based on the number of bedrooms as follows: first bedroom, two persons; each additional bedroom one person. Where higher densities are known, they shall be used.
Kitchens	100 cfm/person 50 cfm/person	Intermittent mechanical exhaust, natural ventilation (opened windows) for control of moisture, odors, gases, vapors, and particles
Garages separate for each dwelling unit	100 cfm/car	Normally satisfied by infiltration or natural ventilation
Common for several units	1.5 cfm/ft ²	

^a Proposed ASHRAE Standard 62-1981R for private dwelling, single, multiple.

Source: American Society of Heating, Refrigerating and Air Conditioning Engineers, Inc., ASHRAE Standard 62-1981R: A Proposed National Standard: Ventilation for Acceptable Indoor Air Quality, Public Review Draft, Atlanta, Georgia, July 15, 1986.

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Section 8

MODELS

INTRODUCTION

Mathematical modeling is an important tool in the field of indoor air quality, both as a means for studying the factors which influence concentrations of indoor air pollutants and as a basis for estimating indoor air pollutant concentrations in homes. A proper understanding of the relative importance of factors such as source emission and air exchange rates as they influence indoor air quality is essential to the development of effective measurement and mitigation techniques. Moreover, since there are more than 80 million residences in the United States today, estimating pollutant concentrations with mathematical models within large numbers of homes is commonly thought to be more practical and cost effective in assessing population exposures than direct measurement of pollutant levels (1).

This section presents descriptions of some representative mathematical models that have been developed to study and predict various aspects of indoor air quality. It also provides examples of how these models have been applied to date. As shown in Figure 8-1, a complex interaction of many factors determines the indoor air quality within a given home (2). In a given model, the level of detail with which each of these factors is assessed depends on the purpose of the model and the availability of data. Typical objectives of indoor air quality models are:

- Provide a method for ranking the relative importance of indoor pollutant sources.
- Quantify indoor concentration distributions within classes of homes based on regional, temporal, source, or other key parameters that may influence indoor concentrations.
- Identify high-risk populations exposed to high indoor pollutant concentrations.
- Provide field study design assistance by determining key parameters to measure and information gaps to fill.
- Provide tools for policy makers involved with energy conservation, new housing codes, acceptable emission rates, etc.
- Identify key parameters to target for control/mitigation efforts.
- Estimate indoor pollutant exposures for epidemiology studies.
- Provide estimates of possible peak exposures of home occupants to indoor pollutants.

In general, there are two basic categories of mathematical models that can be used to predict the concentration of indoor air pollutants:

- Steady-state (Equilibrium) models
- Dynamic (Time-Dependent) models.

Both steady-state and dynamic indoor air quality models are usually developed using the same mass balance approach.

Steady-state models are usually used to predict average concentrations within homes, and are generally less complex mathematically than dynamic models. They are developed using the assumption that variables such as source strength, outdoor pollutant concentrations, air exchange rates, and pollutant reactivity are constant over the time period of interest. Often, steady-state models employ statistical techniques to extrapolate direct monitoring (and other data taken) from a relatively limited number of homes to predict the concentrations of air pollutants in a large number of homes.

Dynamic models are commonly used to predict indoor pollutant concentrations as they vary over time, and are generally more complicated mathematically than the steady-state models. Their principal applications are to predict or measure air exchange rates, peak concentrations, dispersion rates of pollutants indoors, and other time-varying aspects of indoor air quality.

MASS BALANCE APPROACH

Mass balance models begin with a theoretical equation that describes the generation and loss of pollutants within the volume of the home. Experimental data may be used to "fine tune" the value of the parameters used in the theoretical model, but the starting point for the model is the mass balance equation. The level of validity that can be achieved by the models is limited by the complexity that is acceptable to the user, the degree to which the physical/chemical processes are defined, and the precision to which the relevant input factors (such as infiltration rate, building materials, etc.) are defined or known.

Of the four basic processes typically used to model indoor air quality, two act to add to the mass of pollutants in the home:

- Flow of outdoor pollutants to indoors and
- Generation of indoor pollutants

while the other two tend to decrease the indoor pollutant mass:

- Flow of indoor air (with pollutants) to outdoors and
- Removal of indoor pollutants by mechanisms other than ventilation.

The house, for the simplest models, can be viewed as a single compartment. For the most general application, the mass balance equation is written in a differential form. However, to introduce the concepts, some simplifying assumptions can be made. If the processes outlined above were constant and non-changing over time, the equation to describe conditions for a particular pollutant could be written as:

$$AC_i + RC_i - AC_o + \frac{S}{V} \quad (8-1)$$

where:

A	=	air exchange rate (ACH), 1/time
C _i	=	indoor concentration of pollutant, mass/volume
R	=	reactivity rate (chemical & physical removal), 1/time
C _o	=	outdoor concentration of pollutant, mass/volume
S	=	source emission rate, mass/time
V	=	volume of house or room, volume

The first term on the left side of the equation represents the flow of indoor pollutants leaving the house. The second term is the amount removed by processes such as chemical reactions and physical removal with filtering devices.

On the right side of the equation, the first term is the amount of pollutant entering from outdoors (ambient). The second term signifies the rate at which the contaminant is generated with respect to the volume of the compartment.

Equation 8-2 can be rewritten as:

$$C_i = \frac{AC_o + \frac{S}{V}}{A + R} \quad (8-2)$$

This can be applied to a room or whole house. Efforts to improve upon this basic model focus on a number of simplifying assumptions that were made in developing the equation. Some of these assumptions include:

1. Time Independence--Equation 8-2 assumes that the values used for each dependent variable in the equation remain constant for a substantial time period and the dependent variables are not sufficiently correlated to substantially affect the indoor concentration. Thus,

"equilibrium" (or "steady-state") conditions are assumed. Some models reflect the fact that many of the variables in Equation 8-2 do, actually, change with time and are called "dynamic" models.

2. Complete Mixing--In Equation 8-2, the house is viewed as a single compartment in which the concentration of the pollutant does not vary spatially. This assumption is valid if (1) the air is well mixed or (2) the concentration of air being removed from the indoor space is close to the average concentration of the space. Complete mixing is not always achieved, especially when considering short time periods or reactive pollutants. "Multi-compartment" models have been developed in an attempt to better simulate incomplete mixing. A space (whole house or even a single room) may be arbitrarily divided into a number of compartments or zones. A series of mass-balance equations are then applied to account for the interactions between the zones.
3. Reactivity Represented as a Single Parameter--The removal mechanisms, other than mass movement of the pollutant from a zone, consist of the following:
 - Chemical conversion of a pollutant to another species
 - Deposition (in the case of particles)
 - Adsorption on to surfaces
 - Absorption into materials.
4. Active Air Cleaning--If there is active air cleaning in the space, this needs to be accounted for in Equation 8-2.

Some models use equations to describe in more detail these individual removal mechanisms instead of using one value to represent a combined effect.

There are several variations of the above-described modifications that are employed in different models. In many cases, simplifying assumptions are made to make the modifications easier to apply.

EQUILIBRIUM MODELS (TIME INDEPENDENT)

Equilibrium models are used to predict concentrations (or other parameters) that have stabilized at some steady-state value. An underlying assumption in using a steady-state equation is that all the factors that affect concentration are constant, or, at a minimum, not significantly correlated. In reality, in typical conditions, few of the factors are constant, but they may sometimes be

considered as such for the sake of evaluating average conditions. As an example, a kerosene heater or a gas range burner may be approximated as a steady-state source for the duration of its use. A gas oven, however, does not fit as well into this category because it operates full-on for the warm-up period (at one rate) and then operates in a cyclic fashion on and off (at another "average" rate) to maintain the set temperature.

Simplifying assumptions may be made so that many of these parameters may be regarded as constant if they are not correlated. For instance, depending on the intended purpose of the model, gas stoves may be considered as steady-state sources based on normal usage patterns. Also, air exchange rates may fluctuate greatly with ambient conditions, but for some modeling purposes, they may be estimated by a constant value. Outdoor pollutant concentrations and indoor reactivity rates usually tend to fluctuate less than emission rates and air exchange rates, and therefore, the assumption of constant value for these parameters generally results in smaller errors.

Steady-state equations are usually applied to general cases where values for long-term (greater than 3 hours) concentrations are sought. When a particular geographic area is being considered, enough similarities may exist between homes so that certain parameters may be combined or "lumped" into a single term. Some parameters may be eliminated from the equation or included in another term.

A model employing some of these concepts was developed by Sexton, et al. at Harvard University (3). The model was designed to approximate average long-term NO_2 levels in electric- and gas-cooking homes in Portage, Wisconsin. It contains no explicit volume term. The ambient and indoor parameters were derived from monitoring programs in six U.S. cities (the "Harvard Six Cities Studies").

A first-order differential equation was used to describe the pollutant mass-balance in a single compartment. The steady-state solution took the form of Equation 8-2, which was subsequently factored into the form of Equation 8-3:

$$C_i = \frac{S'}{A + R} + \frac{AC_o}{A + R} \quad (8-3)$$

where: $S' = S/V, \mu\text{g}/\text{m}^3/\text{hr}$

It was then simplified by lumping parameters so that

$$\frac{S'}{A+R} = a$$

and

$$\frac{A}{A+R} = b$$

Equation 8-3 now takes the form of Equation 8-4.

$$C_i = a + bC_o \quad (8-4)$$

In this form, the term "a" represents an effective indoor source strength and "b" is a "penetration" factor. The value used for "a" was 45 micrograms (μg)/ m^3 in homes with gas cooking and zero in homes with electric-cooking. The penetration factor was 0.6 for all homes, and is the same for gas and electric homes. The estimates of the parameters "a" and "b" were derived from year-long empirical observations of NO_2 values in 25 electric and 112 gas homes in Portage, Wisconsin.

The volume of the home was not considered explicitly in the model but was incorporated into the source strength term. This model assumes a constant NO_2 source strength of 45 $\mu\text{g}/\text{m}^3$ during the time period the source remains on. In this sense, the source term, S' , is not an emission rate, but a concentration derived from empirical data. Because of the empirical nature of this model, the extent of its applicability is unknown, but is expected to be limited.

Several steady-state models were included in the Environmental Impact Statement for The Expanded Residential Weatherization Program issued by the Bonneville Power Administration (BPA) (4). These simplified models were presented as a means for homeowners to estimate their indoor pollution concentrations. Models were developed to calculate pollutant concentrations resulting from formaldehyde outgassing from building materials and furnishing, radon emanation, and the use of combustion devices.

Equation 8-5 was used to describe the average, long-term pollution concentration resulting from combustion sources.

$$C_i = \frac{St}{24AV} \quad (8-5)$$

where:

C_i	=	average daily indoor concentration, mg/m^3
S	=	source emission rate, mg/hr
t	=	time that source is on each day, hr
A	=	air exchange rate (ACH), 1/hr
V	=	volume of home, m^3

Equation 8-5 is actually a variation of Equation 8-2 which is derived as follows. If the outdoor pollutant concentration and reactivity terms are assumed to be zero, then Equation 8-2 can be re-written as follows:

$$C_i = \frac{S}{AV} \quad (8-6)$$

The inclusion of the term "t" controls the "weight" of the source term in Equation 8-5. It represents the time the source is "on." The number 24 in the denominator is a conversion factor carrying the units hr/day.

The outdoor pollution concentration is relatively low and uniform throughout the region (State of Washington area) served by the BPA. In other areas where outdoor concentrations are higher, the equation would have to be modified to include the outdoor contribution.

The reactivity was eliminated from the model also to simplify the calculations. Because this term is often considered a constant in most models, and this model was only used to compute average daily concentrations, the effects of the reactivity term could have been absorbed into the source term. Also, in many cases, the reactivity term is relatively small when compared to the air exchange rate. A notable exception to this rule is NO_2 , which may often be removed from indoor air by reaction at a rate comparable to its removal by air exchange.

A mass balance model was used by Monat and Chin to establish air exchange rates needed to maintain specified concentrations of different pollutants (5). They began with a mass balance equation in the form of:

$$C_i = \frac{\frac{Q}{V} (C_o + \frac{S}{Q})}{\frac{Q}{V} + R} \quad (8-7)$$

where:

C_i	=	steady-state indoor pollutant concentration
Q	=	volumetric flow rate of air
V	=	interior volume of home
C_o	=	outdoor pollutant concentration
R	=	reactivity rate
S	=	source emission rate

By rearranging this equation, its similarity can be compared with another model previously discussed. Considering that, by definition:

$$\frac{Q}{V} - A$$

Equation 8-7 can be shown as:

$$C_i = \frac{AC_o + S/V}{A + R} \quad (8-8)$$

In this form, the equation is the same as Equation 8-2.

Equation 8-7 was rearranged to solve for the air changes per hour needed to maintain the indoor pollutant concentration at a desired level (6).

$$\frac{Q_{min}}{V} = \frac{\frac{S}{V} - C_i R}{C_i - C_o} \quad (8-9)$$

where: Q_{min} = optimal air infiltration rate

The value of Q_{min}/V represents the minimum air changes per hour (ACH) required to sustain indoor pollutant levels within certain standards. Any amount greater than that would tend to reduce the pollutant concentration more. However, as values for air exchange rates increase, so does energy expense. Table 8-1 shows the values used for the parameters in Equation 8-9 and the corresponding results for various situations.

Drye, et al. used a linear regression analysis to analyze NO_2 field measurements in gas-cooking homes from five U.S. metropolitan areas (7,8). The possible relationship between bedroom NO_2 levels and the (regional) siting of the home, the season of the year, ambient (outdoor) NO_2 levels, and the presence of gas pilots was investigated.

The model used in this investigation was developed using Equation 8-4:

$$C_i = a + bC_o$$

In order to provide a basis for modeling the effects of seasonal variations (which affects the air exchange rate), siting (style and type of home construction), and gas pilots, a linear expansion of Equation 8-4 was formulated:

TABLE 8-1. MINIMUM AIR EXCHANGE RATES NEEDED TO MEET CERTAIN STANDARDS
(AS DETERMINED BY EQUATION 8-9 FOR A HOUSE VOLUME OF 10,000 FT³)

POLLUTANT	C _i ^a	C _{ss}	SOURCE	S (mg/hr)	Q _{air} /V for V=283.2 m ³ (ACH)
Particulates	82 µg/m ³	5mg/m ^{3b}	6 Cigarettes	23.0	0.10
NO ₂	45 ppb	5 ppm ^b	Oil Furnace with 10% leakage	per cigarette 4,630	0.20
Particulates	82 µg/m ³	5mg/m ^{3b}	Oil Furnace with 10% leakage	4,540	0.33
CO ₂	3300 ppm	5000 ppm ^b	Respiration of 6 people	66,284 per person	0.45
Radon Gas	--	--	Building Materials Earth, Ground Water	--	0.50
NO ₂	45 ppb	5 ppm ^b	Gas Range (Propane) On Continuously	2,179	0.81
SO ₂	19 ppb	5 ppm ^b	Oil Furnace with 10% leakage	65,376	1.70
Hydrocarbons	0	0.24 ppm ^c	Oil Furnace with 10% leakage	1,362	3.00
Ammonia	0	50 ppm ^b	Floor Cleaner	91,254	9.00
Hydrocarbons	0	0.24 ppm ^c	Enamel, 1/2 gallon	(238,350 mg/gal)	388
ASHRAE Ventilation Requirement for 4 Occupants; General Living Quarters					0.48
ASHRAE Ventilation Requirement for 4 Occupants; Kitchens and Baths					0.12

^a Boston, Massachusetts values, 1978

^b OSHA Standards

^c National Ambient Air Quality Standards

Source: Monat, J.P., and R.H. Chin, Minimum Acceptable Infiltration Rates for Buildings, Walden Division of
Abcor, Inc., Wilmington, Massachusetts, n.d.

$$C_i = B_0 + B_1 C_o + B_2 (SEAS) + B_3 C_o (SEAS) + B_4 (PILOTS) + B_5 (SITE) +$$

$$B_6 C_o (SITE) + E \quad (8-10)$$

where: SEAS = 0 (summer) or 1 (winter)
 PILOTS = 0 (no gas pilots) or 1 (gas pilots present)
 SITE = 0 or 1 (depending on the site)
 E = Model error term

The empirical coefficients $B_0 \dots B_6$ were derived from seasonal ambient and bedroom NO_2 concentrations, and structure-specific information contained in the data set.

The resulting model provided the following empirical equations for bedroom NO_2 concentrations:

SUMMER:	(pilots)	C_{BED}	=	11.55 + 0.67 C_o
	(no pilots)	C_{BED}	=	3.79 + 0.67 C_o
WINTER:	(pilots)	C_{BED}	=	17.52 + 0.53 C_o
	(no pilots)	C_{BED}	=	9.76 + 0.53 C_o

It was observed that homes without gas-pilots were consistently lower in NO_2 concentrations than homes with gas pilots. It was also observed that winter NO_2 levels were higher than in summer, a fact attributed to both lower expected air exchange rates (due to more frequently closed windows and doors) and greater use/misuse of secondary heating sources which emit NO_2 . A logit model for predicting the distribution of bedroom levels for a given ambient level was developed by a direct fit to the data. These data are shown in Figure 8-2.

An important use of the source strength and emission rate measurements (see Section 3, Emissions from Combustion Sources) as well as pollutant concentrations and air exchange rate data collected in monitoring programs (see Section 5, Indoor Concentrations) is in the development of models for predicting pollutant concentrations across populations of homes around the country. Such data provide reasonable values for key parameters in modeling efforts designed to clarify and expand upon indoor air quality policy options.

For example, it has been inferred that in homes where unvented gas space heaters are the primary heating source, indoor NO_2 concentrations will be highest at times when the indoor/outdoor temperature difference (and, therefore, heater usage) is greatest. Research has indicated that unvented gas space heaters exhibit relatively high NO_2 source strengths under typical operating conditions (see Section 3, Emissions from Combustion Sources) because they are generally unvented, and such appliances typically exhibit relatively high NO_2 emission rates. This implies that data on indoor/outdoor temperature differences might be useful in predicting indoor NO_2 concentrations in homes where unvented gas space heaters are the main heating source.

Figure 8-2. Predicted and Actual Percent of Bedrooms with an NO_2 Concentration Exceeding 53 ppb--Winter

Source: Drye, E.E., et al., "Development of Models for Predicting the Distribution of Nitrogen Concentrations," presented at the 81st Annual Meeting of Air Pollution Control Association, Dallas, Texas, June 19-24, 1988.

Using this thesis, Hemphill, et al. measured indoor/outdoor temperatures and indoor concentrations in a group of 82 homes in which unvented gas space heaters were the main heating source (9). Based on this data, a statistical correlation was developed which described a linear relationship with the indoor/outdoor temperature difference and indoor NO₂ concentrations:

$$C_i = -82.17 + 24.55 \Delta T \quad (8-11)$$

This correlation confirms the expectation that NO₂ concentrations in these homes will increase as the indoor/outdoor temperature difference increases. In parallel with the statistical correlation developed above, a separate physical model was developed from Equation 8-2 assuming that the contribution of outdoor NO₂ to indoor concentration levels is essentially zero:

$$C_i = \frac{\frac{QE}{V}}{A+R} \quad (8-12)$$

where:

Q	=	heat demand, J/hr
E	=	emission rate, g NO ₂ /J
V	=	volume, m ³
A	=	air exchange rate, 1/hr
R	=	first order reactivity, 1/hr

The source strength, S, for the unvented gas space heater is expressed here in terms of the product of the heat demand (or firing rate), Q, and the emission rate, E, of the heater. In order to estimate the amount of heat required by the homes in the study area, the heat demand was described as a function of the amount of heat lost through convective and conductive heat losses from the homes:

$$Q = \Delta T (C_p VA + \frac{H}{(V/A)}) V \quad (8-13)$$

where:

C _p	=	heat capacity of air, J/m ³ /°C
H	=	conductive heat loss from walls, J/m ² /°C/hr

Inserting the proper values for the conductive heat loss through walls in residential buildings and the standard heat capacity for air, Equation 8-13 becomes:

$$Q - \Delta T (1190A + \frac{2040}{(V/A)}) V \quad (8-14)$$

Substituting this expression into Equation 8-12 yields:

$$C_i = \frac{E}{V} \frac{1}{(R+A)} (1190A + \frac{2040}{(V/A)}) \Delta T \quad (8-15)$$

where: E = NO₂ emission rate, g/J

This physical model suggests a linear relationship between indoor NO₂ concentrations and the indoor/outdoor temperature difference, as does the statistical correlation developed previously. Moreover, when typical values were entered into Equation 8-15 for the emission rate of unvented gas space heaters (E), ratio of home volumes to wall areas (V/A), air exchange rates (A), and reactivity rates (R), good agreement was found between the results of the physical approach and the statistical correlation developed from real data.

The physical model was used to estimate distributions of indoor NO₂ concentrations in homes in two cities with similar housing characteristics but different climates. As expected, higher NO₂ concentrations were predicted in the homes studied when the indoor outdoor/outdoor was greatest. However, the predicted concentrations exhibited a broad distribution, suggesting that personal habits of occupants and characteristics of construction of particular homes may play a large role in influencing exposures. Based on the results of this modeling effort, it was concluded that control strategies based on the use of low-emission heaters or improved insulation in homes may be fruitful.

Traynor, et al. developed a comprehensive steady-state indoor air quality model as part of a larger "macro-model," which included submodels for estimating air-exchange and source usage throughout homogeneous housing stocks (2). This model was unique in the level of detail employed and the use of basic housing and appliance data as inputs to the model. The indoor air quality model was developed on the basis of a one-week average pollutant concentration and complete mixing of household air. Initial modeling efforts were restricted to the following pollutants: CO, NO₂, and RSPs.

The mass balance equation employed in this model was of the same form as Equation 8-3:

$$C_i = \frac{PAC_o + S/V}{A + R} \quad (8-16)$$

where:

P	=	the penetration factor, or the fraction of outdoor contaminants that penetrate the building shell
V	=	interior volume of home
R	=	reactivity
A	=	air exchange rate
C _o	=	outdoor pollutant concentration
S	=	source emission rate

The source strength, S, and the air exchange rate, A, were further defined as sub-models in this effort.

The source strength was described as a product of three variables:

$$S = QEF_v \quad (8-17)$$

where:

Q	=	source usage rate
E	=	source emission rate
F _v	=	appliance venting factor

The source usage rate, Q, was described as being equal to the heat loss from the home through conduction and infiltration minus the "free" heat (heat generated by other indoor sources), all modified by an appliance efficiency and lifestyle factor:

$$Q = \frac{b}{e} (UA\Delta T + \alpha Vq\Delta T - Q_f) \quad (8-18)$$

where:

b	=	lifestyle factor
e	=	appliance efficiency
U	=	building shell thermal conductance
A	=	total home surface area
ΔT	=	indoor/outdoor temperature difference
α	=	air exchange rate
V	=	house volume
q	=	heat content of dry air
Q _f	=	house "free" heat

Free heat generated within a home was considered to consist of solar heat gain, heat generated by appliances, and heat given off by home occupants:

$$Q_i = Q_s + Q_{appl} + Q_{people} \quad (8-19)$$

Overall building thermal conductance, surface area, and volumes were calculated from information provided by utility surveys and standard references for various building materials.

The air exchange rate submodel was expressed as a function of the effective leakage area of the home (ELA), the indoor/outdoor temperature difference (ΔT), stack and wind parameters (f_s and f_w), wind speed (v), wood stove flue flow rates (Z_{appl}), and house volume:

$$\alpha = \frac{(ELA^2 f_s^2 \Delta T + ELA^2 f_w^2 v^2 + Z_{appl}^2)^{0.5}}{V} \quad (8-20)$$

The stack and wind parameters were calculated from standard reference conditions, while wood stove flue flow rates were provided by previously published data.

Admitted weaknesses of this model included the lack of algorithms for modeling increased natural ventilation during mild weather conditions (i.e., open windows and doors) and the use/substitution of secondary heat sources, activities which are both related to occupant behavior.

Required data inputs to this model consisted of two distinct types: regional and global. Regional data consisted of parameters considered most likely to vary from region to region in the United States: outdoor temperatures, house volumes and numbers of stories, and appliance market penetration and usage data. Global parameters included those data which were not expected to vary from region to region. These included source emission rates, degree of venting from specific combustion sources, pollutant penetration factors, and pollutant reactivity rates.

Although the data available were not deemed sufficient to fully characterize the housing stocks of interest, a number of modeling runs were performed to provide qualitative indoor air quality predictions. In particular, modeling runs were performed to investigate the following:

- The effect of venting combustion sources on NO_2 concentrations in Southern California homes.
- The effect of gas stove usage on indoor NO_2 concentrations.
- The effect of outdoor temperatures on NO_2 concentrations in homes with kerosene heaters (see Figure 8-3).

Figure 8-3. Indoor NO₂ Concentration vs. Outside Temperature In Houses with Kerosene Heaters in the Rochester, (NY) Gas & Electric Region, with an Outdoor NO₂ Concentration of 0.008 ppm (GSD = 1.4).

Source:

Traynor, G.M., et al., Macromodel for Assessing Residential Concentrations of Combustion-Generated Pollutants: Model Development and Preliminary Predictions for CO, NO₂, and Respirable Suspended Particles, Report No. LBL-25211, Lawrence Berkeley Laboratory, Berkeley, California, January 1989.

- The effect of varying home specific leakage area (SLA) on the concentration of NO_2 in homes with gas stoves/ovens and kerosene heaters. SLA is a measure of the "tightness" and energy efficiency of a home.
- The effect of SLA on the indoor CO concentration in homes with convective unvented gas space heaters (UVGSH) and gas ranges/ovens.
- The effect of various CO emission rates from UVGSH's on home CO concentrations.
- The effect of smoking on indoor RSP concentrations.
- The relative impacts of particular combustion sources on indoor air quality (see Figure 8-4).

This model was concluded to be successful in delineating the relative impact of various indoor combustion sources on indoor air quality and to assess indoor air pollutant concentrations from combustion sources. In particular, the following model predictions were noted:

- High indoor RSP concentrations are associated with indoor smoking, the winter-time use of non-airtight wood stoves, oil-burning furnaces, radiant kerosene heaters, and convective unvented gas space heaters.
- High CO and NO_2 concentrations are associated with the winter-time use of unvented gas and kerosene space heaters.

Overall comparison of the model results with previously conducted field studies indicated that the current state of the model was sufficient to produce at least order-of-magnitude indoor air quality assessments. However, further improvement of the model predictions was cited as being hindered by the lack of adequate data on field emission rates from combustion sources, the extent of the presence of other combustion sources (i.e., attached garages and fireplaces) in the housing stocks modeled, and the effect of lifestyle on indoor air pollution concentrations. It was recommended that future field studies be performed to address these data gaps.

DYNAMIC MODELS (TIME DEPENDENT)

Indoor pollutant concentrations may vary widely from time to time. Steady-state equations are sometimes used to predict average human exposure, but are incapable of predicting time dependent characteristics, such as peak concentrations. One of the reasons that both types of models are useful is that for some pollutants, peak concentrations are more critical, while for others long-term average concentrations are more important. Transient or dynamic models are needed for modeling peak concentrations.

In a dynamic model, simulation of a gas oven cycling on and off may be done using a sinusoidal input. An intermittent source being turned on and off at different times may also be modeled.

Figure 8-4. Modeled Indoor RSP-Concentration Distributions in Houses with Only One Indoor Combustion Pollutant Source. The Rochester (NY) Gas & Electric Region Was Used for the Analyses, with an Outdoor Temperature of 0°C . Outdoor RSP Concentration GM was $19 \mu\text{g}/\text{m}^3$ (GSD = 1.5).

Source: Traynor, G.W., et al., Macromodel for Assessing Residential Concentrations of Combustion-Generated Pollutants: Model Development and Preliminary Predictions for CO , NO_2 , and Respirable Suspended Particles, Report No. LBL-25211, Lawrence Berkeley Laboratory, Berkeley, California, January 1989.

There is always a distinction between the steady-state and transient (time-varying) portions of the models. They have different functions and dominate over the results at different times. For continuous sources, as time increases, the transient portion "dies out" and the results approach the steady-state value asymptotically. The steady-state portion usually resembles the type of steady-state equations in the preceding section.

Dynamic models, in general, are usually more flexible than steady-state models. Because time is a factor in the dynamic equation, parameters may be allowed to vary in intensity over time, thus changing their impact, with respect to the other parameters, on the outcome.

A typical dynamic indoor air quality model was used by Lawrence Berkeley Laboratory to determine pollutant emissions from gas stoves and unvented gas-fired space heaters (10). Originally, the model was developed to describe particles, but studies have indicated that the model is applicable to gases as well.

Equation 8-21 is derived from the more generalized differential mass balance equation as expressed by Equation 8-18. This differential equation has an added "penetration" factor to represent that portion of the outdoor pollutants which pass through the shell into the house.

$$dC_i = PAC_o dt + \frac{S}{V} dt - (A+R) C_i dt \quad (8-21)$$

where:

C_i	=	indoor contaminant concentration, $\mu\text{g}/\text{m}^3$
C_o	=	outdoor contaminant concentration, $\mu\text{g}/\text{m}^3$
P	=	fraction of outdoor contaminants that penetrate the shell (unitless) (1 ~ 100% penetration)
A	=	air exchange rate in air changes per hour (ACH), 1/hr
S	=	generation rate of indoor contaminants, also called source strength, $\mu\text{g}/\text{hr}$
V	=	chamber volume, m^3
R	=	net rate of removal processes other than air flow, 1/hr

Complete mixing of the indoor air is assumed in this model.

Holding C_o , P , A , S , and R constant, Equation 8-21 was solved for the indoor pollutant concentration, $C_i(t)$ as a function of time. Equation 8-22 is classified as a single compartmental, dynamic (transient) equation.

$$C_i(t) = \frac{PAC_o + S/V}{A + R} [1 - e^{-(A+R)t}] + C_i(0)e^{-(A+R)t} \quad (8-22)$$

The units for C and C_o are $\mu\text{g}/\text{m}^3$, while the units for S are $\mu\text{g}/\text{hr}$ for particles. When the pollutant is a gas, such as NO_x , CO , and CO_2 , the units for C and C_o are in parts per million (ppm) and S is in cubic centimeters per hour (cm^3/hr). The term "e" is the base of natural logarithms and is a constant. The volumetric concentration is independent of temperature and pressure. It is used for gases because the results are more easily interpreted.

The steady-state version of Equation 8-21 is Equation 8-2.

$$\frac{PAC_o + \frac{S}{V}}{A + R}$$

The transient portion consists of:

$$- \left[\frac{PAC_o + \frac{S}{V}}{A + R} + C_i(0) \right] e^{-(A+R)t}$$

The model reaches 95 percent of steady-state conditions after 2.5 hours for a gas with a reactivity rate of 0.15 hr^{-1} , and an air exchange rate of 1 air change/hr (ACH). If the air exchange rate were as low as 0.25 ACH, as in a "tight" home, concentration would climb for 7 hours until 95 percent steady-state conditions were achieved. Other pollutants appear to be more reactive in the indoor environment, such as particulates and formaldehyde, so that they reach steady-state more quickly than NO_2 . CO , however, is less reactive and, hence, reaches a steady-state level later.

Experiments were performed using a gas oven in a 27 m^3 test chamber. When a mixing fan was not used, this model slightly underestimated the actual NO_x concentration for the first hour, as evident from Figure 8-5. It was assumed that the emissions plume passed the sampling probe before completely mixing within the chamber air-space. When the mixing fan was employed, however, the modeling results predicted the actual indoor NO_x concentration very closely throughout the two-hour period (see Figure 8-6). It was necessary, though, to calculate two pollutant source strengths. The first one applied to the initial 11-minute warm up and the second one was used from 11 minutes to the end of the hour. After one hour, the source term was changed to zero and the initial indoor concentration set at the one hour level.

Figure 8-5. Calculated and Measured NO_x Concentration Profiles Without Chamber Mixing

Source: Traynor, G.W., Anthon, D.W., and Hollowell, C.D., "Technique for Determining Pollutant Emissions from a Gas-Fired Range," Atmospheric Environment, Vol 16, pp. 2979-2987, 1982.

Figure 8-6. Calculated and Measured NO_x Concentration Profiles with Chamber Mixing

Source: Traynor, G.W., Anthon, D.W., and Hollowell, C.D., "Technique for Determining Pollutant Emissions from a Gas-Fired Range," Atmospheric Environment, Vol 16, pp. 2979-2987, 1982.

Ryan, et al. from the Harvard School of Public Health, used a simple model to estimate NO₂ concentrations from a gas stove and a kerosene heater and SO₂ concentrations from a kerosene heater (11). Their model was found to be the simplest approach that accounts for all the essential physical and chemical processes expected in the indoor environment.

The differential equation used to describe the rate of change of pollutant concentration with respect to time is shown below.

$$\frac{dC_i}{dt} = A(C_o - C_i) - RC_i + S \quad (8-23)$$

where: C_i = indoor pollutant concentration, $\mu\text{g}/\text{m}^3$
 C_o = outdoor pollutant concentration, $\mu\text{g}/\text{m}^3$
 A = air exchange rate (ACH)
 R = pollutant reactivity, 1/hr
 S = source term, $\mu\text{g}/\text{m}^3\text{-hr}$

Holding A , C_o , and R constant, and solving for the indoor concentration as a function of time yields:

$$C_i(t) = \frac{S'}{A} (1 - e^{-At}) + C_i(0)e^{-At} \quad (8-24)$$

where:

$$S' = S + AC_o$$

This equation is identical to Equation 8-22 with the volume and reactivity terms removed. Here, the volume is incorporated into the source term.

Results of this model were compared to mean concentrations of NO₂ in a Vermont residence. Considering a mixing volume of 350 m³ and an air exchange rate somewhat less than 1.0 ACH, the model produced a steady-state concentration in good agreement with the observed mean values. The authors state that "more detailed modeling would require time-dependent air exchange measurement and source terms but would not be expected to improve the results qualitatively."

In single compartment modeling equations, a high degree of air mixing is a prerequisite to obtaining a satisfactory correlation between predicted and actual indoor pollutant concentrations. In situations where incomplete mixing is suspected, a mixing factor has been introduced into some modeling equations to compensate for this.

MULTI-COMPARTMENT MODELS

Whenever a space has non-uniform mixing, indoor air quality is more difficult to predict. Buildings with multiple rooms and even rooms with forced air supply may require multi-compartmental analysis. The ventilation air introduced into the space may be ineffective in removing or mixing contaminants and stagnant zones may exist.

Multi-compartment models are used when air spaces are non-uniformly mixed. The evaluation of air flow rates between compartments is difficult to establish, therefore, making multi-compartment modeling much more difficult than single compartment modeling, even in steady-state cases. Each of the individual compartments in multi-compartment models is assumed to be uniformly mixed.

In a residence, each room could be considered as a single compartment. If a large room existed with poor mixing, the room itself could be broken down for modeling purposes into several compartments. Air flow rates between compartments must then be calculated and a series of equations must be executed, a process which lends itself to computer solutions due to the large number of calculations that must be done.

Detailed discussion of these complex models is beyond the scope of this handbook. For detailed descriptions of multi-compartment models, see Indoor Pollutants (12).

At Harvard University, indoor air quality modeling has been approached from the standpoint of compartmental analysis considering reactive chemistry (13). To aid in developing models, data were gathered on indoor and outdoor pollutant levels. In addition, tracer gas studies were conducted to investigate the vertical and horizontal variability of concentrations inside a kitchen. The models developed were designed to characterize and simulate the observed distribution of pollutants and tracers inside the kitchen. The models only addressed reactions of oxides of nitrogen.

Because of the nature of multi-compartmental equations and the fact that indoor air quality has only recently been modeled for non-industrial, occupied spaces, much work needs to be done regarding the accuracy of the factors used in these equations. Difficulties include the following:

- The net generation rates of pollutants must be carefully determined for the individual sources.
- Reactivity rates need to be ascertained for each pollutant considered.

- Active removal rates (such as filtering) need to be calculated.
- Ventilating effectiveness by natural and mechanical methods for each room or compartment as well as the whole house or building must be known.

If these parameters are not carefully determined, the results obtained using multi-compartmental models may be inaccurate.

SENSITIVITY ANALYSIS

Of the models presented in this section, Equation 8-22 was selected to investigate the sensitivity of indoor pollutant concentrations, specifically NO_2 , to the various factors that affect it. This equation is repeated here for reference:

$$C_i(t) = \frac{PAC_o + SV}{A + R} [1 - e^{-(A+R)t}] + C_i(0)e^{-(A+R)t}$$

The advantages of this model are:

- Broad applicability
- Relative simplicity
- Accuracy in predicting concentrations.

The major disadvantage is that complete mixing is assumed. However, for time periods of several hours or more, the errors resulting from this assumption are small for a given set of parameters.

The equation was solved using a reactive pollutant (in this case NO_2) for a typical case listed in Table 8-2. Note that the values for S indicate the range typical for gas cook tops only. The typical values were used in Equation 8-22, and C_i was solved for times $t = 60, 120, \text{ and } 180$ minutes. The results of these analyses are shown in Figures 8-7, 8-8, and 8-9.

Each of the five vertical lines on these figures represents a range of concentrations with all parameters but one held fixed. Time, t , was set at the value identified. All other model parameters except the one listed below each individual vertical line in the figure were set equal to the typical value shown in Table 8-2. The parameter listed under each individual vertical line in the figure was then set at the high value and then the low value, and C_i was determined in each case. The dot on each line represents the concentration when all parameters are at their typical values. Thus, one can quickly inspect these figures and identify the relative magnitude of the effect of varying any single input parameter between reasonable high and low values while all other conditions remain constant.

TABLE 8-2. PARAMETER VALUES USED IN SENSITIVITY ANALYSIS

Parameter	Typical Value	High Value	Low Value	Units
C_o	30	560	10	$\mu\text{g}/\text{m}^3$
$C_i(0)$	20	20	20	$\mu\text{g}/\text{m}^3$
P	1.0	1.0	1.0	---
A	0.75	1.5	0.25	1/hr
S	207	357	85	$\mu\text{g}/\text{hr}$
V	455	675	227	m^3
R	0.15	0.42	0.02	1/hr

From an inspection of these figures then, the relative ranking of the importance of the model parameters for NO_2 for the general case are:

1. Source emission rate
2. House volume
3. Outdoor concentration
4. Air change rate
5. Reactivity

These results are dependent on the assumptions for the high and low values used in Table 8-2. The range of input values used for outdoor concentration of NO_2 may be misleading. Actually, few homes are exposed to outdoor concentrations as high as $560 \mu\text{g}/\text{m}^3$. However, homes in large cities may be exposed to this outdoor level for short periods. For rural homes, an average value of $20 \mu\text{g}/\text{m}^3$ may be more appropriate, which would make outdoor concentration the least significant factor for rural houses. Additional conclusions which can be derived from this analysis are:

- The source strength has a dominant effect on NO_2 concentration. The source strength is directly proportional to the concentration; as source strength increases so does the concentration, and as the source strength decreases, so does the pollutant concentration. The reactivity of NO_2 and the overall air exchange rate have little impact on peak concentrations, but are important in determining long-term levels.

Figure 8-7. Sensitivity Analysis at $t = 1$ Hour

Figure 8-8. Sensitivity Analysis at t = 2 Hours

Figure 8-9. Sensitivity Analysis at t = 3 Hours

- Individual pollutants will react in varying degrees. Some pollutants do not react indoors, and in those cases, reactivity will not affect pollutant concentrations.

Again, these conclusions are based on model predictions and generally support experimental results. The relative importance of individual factors is not as easy to identify among a large number of experiments or tests carried out under non-uniform conditions.

COMPARISON TO TRACER GAS STUDY

The single compartment model selected relies on the assumption of complete spatial mixing of an emitted contaminant. Some experiments have shown, however, that complete mixing is not always achieved. For instance, an experiment using tracer-gas (SF_6) in a residence showed considerable variation between rooms (14).

A comparison was made, and is presented here, between the results of that experiment and the selected model (Equation 8-22). Using the values listed below, the model results were compared to a typical decay distribution shown in Figure 8-10.

C_o	=	0.0 ppm
$C_i(0)$	=	5.0 ppm
A	=	0.25 ACH
S	=	0.0 cm^3/hr
V	=	420 m^3
R	=	0.0
P	=	1.0

In the actual test, the tracer gas was uniformly mixed through the air handling system so that the same SF_6 concentration was measured at all 12 sampling locations. The air handling system was then shut off and the decay of SF_6 was monitored for at least 6 hours.

The results predicted by the model are shown to fall centrally within the range of values, indicating that it can be used to represent typical conditions up to 7 hours after the source was shut off. Although one must be careful in comparing experimental results using a non-reactive trace gas to draw conclusions for indoor air pollutants, the results of this study and others reported in this section generally support the usefulness of models for estimating the concentration to which an individual who is assumed to be moving randomly through the house is exposed (i.e., is not always in the room with the highest or lowest concentrations).

Other studies have shown experimental results that indicate much more uniformity than is evidenced in this tracer gas study in which there are significant differences in the concentrations between rooms of the house.

Figure 8-10. Comparison of Model Results to Maldonado and Woods Tracer Gas Study

Source: Woods, J.E., E.A.B. Maldonado and R.R. Crawford, "Calculation Methods to Assess Indoor Air Quality," presented at ASHRAE Annual Meeting, June, 1983.

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Section 9

PERSPECTIVE FOR HOMEOWNERS

To date, few efforts have been made to digest available information on indoor air quality from combustion sources for non-technical readers who may be concerned about indoor air pollution in their own homes. The purpose of this section is to help fill that information gap and give homeowners a perspective on the problem.

This section provides some answers to a number of commonly asked questions about indoor air quality from combustion sources, followed by a review of the factors which affect pollutant levels in indoor air, and a description of how control measures are used to alter these factors in favor of improved air quality.

INTRODUCTION

Frequently, homeowners have specific questions with regard to how the issue of indoor air quality pertains to them. Some answers to commonly asked questions are provided below.

- q. Why should I be concerned about indoor air pollutant levels from appliances such as fireplaces or kerosene-fired space heaters?
 - a. The pollutants produced by common household combustion sources are known to have significant adverse health effects when they are allowed to accumulate to certain levels (concentrations) in the air. Since many people spend a large proportion of time indoors, it is in the interest of homeowners to keep the levels of these pollutants to a minimum.
- q. What kinds of pollutants are generated by combustion sources, and which indoor air pollutants should I be most concerned about?
 - a. Many indoor air quality researchers concentrate their efforts on the study of nitrogen oxides, carbon monoxide, and respirable suspended particles, all of which are produced by combustion sources. The term nitrogen oxides refers to a number of compounds such as nitric oxide, nitrogen dioxide, nitrous oxide, etc. Carbon monoxide is often referred to by its chemical formula CO, while the acronym RSP is used for respirable suspended particles, which are particles small enough to be inhaled deeply into the lungs. Although there are many other pollutants (usually in much smaller quantities) that can be produced by combustion, nitrogen oxides, carbon monoxide, and respirable suspended particles are important for three reasons:

- They are primarily products of combustion and are not generated by other pollutant sources.
- They can have serious health effects.
- They are the most well-understood combustion-generated pollutants.

It is important to understand that combustion is not the only source of indoor air pollutants. Indoor air quality can be affected by materials in a home, chemicals used for cleaning or other purposes, moisture, soil under and around the home, and even the activity of people in the home. However, combustion-generated pollutants are an important group and can be considered separately from other indoor air pollutants.

q. How can I find out if I have elevated pollutant levels in my home?

- a. Unfortunately, it is usually difficult for the homeowner to assess the level of indoor air pollutants. The only commonly accepted method of determining air pollutant levels in homes is by direct measurement of concentration using monitoring equipment, a process which can be too expensive for many homeowners to perform adequately at this time. This is partly because the levels of combustion-generated pollutants most commonly expected to exist in homes are lower than those for which inexpensive monitoring devices have been developed.

One of the major difficulties in predicting indoor air pollutant levels in homes is the variability of emissions from combustion sources. This is especially true with regard to carbon monoxide and particle emissions, which may vary substantially not only from appliance to appliance, but even from time to time for the same appliance. Factors which may lead to such variability include how well the flame in the appliance is "tuned", the quality of the fuel being burned, and the cleanliness of the burner. Since less uncertainty is associated with the prediction of nitrogen oxides emissions, a method for estimating peak concentrations of nitrogen dioxide is presented in Appendix B of this handbook.

q. What can I do to improve the indoor air quality in my home?

- a. There are a number of ways to minimize the levels of combustion-generated air pollutants in the home. These methods vary over a wide range of costs and degrees of

difficulty. To implement these measures most effectively, the homeowner needs insight into the factors which influence air pollutant levels indoors.

The following section provides a brief overview of the factors that have been found to be important in determining combustion-generated indoor air pollutant levels in homes. Control measures available to the homeowner are described later in this section.

FACTORS AFFECTING INDOOR AIR QUALITY

The indoor concentration of a pollutant depends on several factors that affect the generation, dispersion, and removal of pollutants. The generation of pollutants is affected by the number of combustion sources present, the emissions from each source, and whether the source is vented to the outdoors. The dispersion of pollutants throughout a home depends on the effectiveness of air circulation within the home and the volume (size) of the home itself. Increased air exchange and the reactivity of certain pollutants indoors tend to remove pollutants from the indoor air. These factors are discussed in more detail below.

Pollutant Source Strength

The effective source strength of pollutants within a home depends on the number of sources present, the emission rate of each source, the amount of time each source is operated, and the manner in which each source is vented. In general, larger source strengths tend to elevate pollutant levels indoors.

Gases, vapors, and particles can be emitted from a number of indoor sources, which include:

- Gas-fired appliances
- Unvented gas-fired space heaters
- Unvented kerosene-fired space heaters
- Lighted tobacco products
- Wood or coal stoves and heaters
- Car engines operating in attached garages.

The number and type of combustion sources within a home are important in determining the overall pollutant source strength in that home. The sources listed above can all be significant under certain circumstances, such as when air exchange rates are very low.

Source Emission Rate

Of equal importance to the number of sources present within the home is the effective emission rate of pollutants from each. Emission rates vary widely

among combustion sources, depending on the type of appliance and the way it is operated and maintained. The reported pollutant emission rates for some combustion sources and appliances are presented in Figure 9-1.

As shown in Figure 9-1, pollutant emissions from a given combustion source type can vary widely. In general, the lowest emissions are reported for those sources and appliances that are the best maintained, the best tuned, and those that are newest. In the case of wood heaters, emissions are highest for the older, non-airtight types, and usually occur when they are being reloaded during operation. Whether an appliance is properly tuned has a considerable impact on emissions. For instance, in one test, the carbon monoxide emission rate from a new kerosene heater increased five times above the normal rate when the heater was operated at a reduced wick height (simulating a worn wick). For some sources, such as wood stoves and fireplaces, emission rates are sporadic (as mentioned above) and the types of pollutants generated are highly variable.

Residence Volume

Home volume plays an important role in determining indoor pollutant concentrations. Consider a pollutant source, such as a kerosene heater, emitting at a constant rate. In a large home, the pollutants will be dispersed within a large volume and the resulting pollutant concentrations will be lower. However, in a small room with the doors and windows closed, the same heater emitting pollutants at the same rate will cause pollutant concentrations to be much higher. Conceptually, this is the difference between diluting a cup of chemicals in a bucket of water instead of a barrel. The concentration of the chemical in the bucket will be much higher than in the barrel. Concentration is usually measured in parts per million (ppm) or micrograms per cubic meter ($\mu\text{g}/\text{m}^3$).

Air Circulation

The degree of air circulation (mixing) within a home also affects pollutant concentrations on a room-to-room basis. Short-term peak concentrations may last only a few minutes, but can reach several times the average concentrations. Homes with better mixing tend to have lower peak concentrations.

Factors that increase mixing are opening doors and partitions between rooms and the use of fans and blowers (either localized or whole-house). The procedures used in this section assume that the pollutants are perfectly mixed throughout the house. Experiments have shown that, in general, for time periods on the order of one hour or more, this assumption is reasonable.

Air Exchange Rate

The air exchange rate refers to the rate at which inside air is replaced with outside air, thereby flushing out indoor pollutants over a period of time. This process occurs continuously for all homes. Every home has different air exchange rates at different times. For a particular home, this rate changes depending on outdoor wind speed, opening of doors and windows, and the operation of externally vented appliances, such as fireplaces.

Figure 9-1. Range of Reported Source Strengths for Selected Combustion Sources

Outdoor Concentration of Pollutants

Outdoor pollution concentration has its greatest effect on indoor air quality when homes have a high air exchange rate. In this case, indoor air is being flushed out of the home rather quickly. If outdoor pollutant concentration is low, as in most rural areas, the overall effect will be to cleanse the indoor air (lower indoor pollution concentration). If outdoor pollutant concentration is relatively high, as in many urban areas, there may be little change in the quality of the indoor air, or it can actually become worse.

Reactivity of Pollutants

Inside the home, some pollutants are adsorbed onto surfaces and some react chemically to form other chemicals which may not be as harmful. Nitrogen dioxide is relatively reactive, and is often significantly reduced by the presence of interior furnishings with large surface areas such as thick carpets, carbon filters, and even certain kinds of walls. Particles also tend to settle out on surfaces, and can be effectively removed by filtration. Carbon monoxide has very little reactivity, and usually is not significantly removed by reaction on surfaces in homes.

HEALTH EFFECTS

Following is a summary of what is known about the health effects of nitrogen oxides, carbon monoxide, and respirable suspended particles.

Nitrogen Oxides

A number of oxides of nitrogen are present in air. Nitric oxide (NO), nitrogen dioxide (NO₂), and secondary byproducts such as nitric acid, nitrate aerosols, and others all have a potential to affect human health. Of this group, NO and NO₂ are currently receiving the most attention in the residential indoor environment.

Experts are in good agreement concerning exposures above 25 ppm. Acute exposures to concentrations of 25-100 ppm can cause reversible bronchiolitis, bronchitis, or bronchial pneumonia, usually followed by complete recovery. Concentrations in the 150-200 ppm range can cause severe respiratory distress.

Typical NO₂ concentrations in homes, however, are much less, seldom exceeding 1.0 ppm. Average outdoor levels can be as low as 0.01 ppm in rural environments and as high as 0.05 ppm in large cities. In general, there is evidence that nitrogen oxides (or their derivatives), particularly NO₂, may be harmful to human health at levels of exposure that can occur indoors.

Evidence suggests that there may be an immediate short-term health effect in the form of an increase in airway reactivity (sensitivity) due to exposure to short-term peak concentration of NO₂. This heightened reactivity can make airways more vulnerable to stimulants such as other pollutants and cold or dry air. Individuals with asthma or acute respiratory infections (current or recent) are likely to be most susceptible.

There is evidence for an increased incidence of acute respiratory infections, especially in infants and children, resulting from exposure to NO₂.

possibly augmented by NO. This effect is more likely to follow repeated exposures. There is also evidence that acute respiratory infections in childhood increase the probability that chronic lung disease will develop in adolescence and adulthood, that growth and development of the lung will be retarded, or both.

There is some evidence that NO₂, possibly augmented by NO, impairs lung function in children. The effect is also likely to follow repeated exposures. Were observed changes such as reductions in lung volumes to persist into adulthood, they could cause reduced lung growth or accelerated aging of the lung.

Both NO and NO₂ combine with hemoglobin and reduce the oxygen-carrying capacity of the blood.

Carbon Monoxide

Carbon monoxide (CO) is a colorless, odorless, and tasteless gas. Exposure to high levels causes health effects ranging from impaired mental and physical performance to death. CO can cause tissue hypoxia (oxygen starvation) by binding with blood hemoglobin and blocking its ability to transport oxygen. The product, carboxyhemoglobin (COHb), is an indicator of exposure and the resulting reduction in oxygen-carrying capacity of blood. CO apparently has no deleterious effects other than those caused by carboxyhemoglobin formation.

CO is generated indoors from combustion devices such as gas cooking stoves, kerosene heaters, unvented gas heaters, cigarettes, and wood burning appliances. Peak concentrations of 50 ppm have been found in some kitchens, although typical average indoor levels seldom exceed 4 times the outdoor levels [indoor/outdoor (I/O) ratio = 4]. Because CO is essentially unreactive, the only mechanism for removal from the indoor environment is air exchange with outdoor air. Therefore, if no indoor sources of CO exist, the I/O ratio is usually close to one.

The effects of CO exposure and resulting carboxyhemoglobin formation are essentially identical to those of other factors which reduce oxygen available to body tissues, such as chronic lung diseases, disorders reducing blood circulation, and high altitude.

- In the short term, carboxyhemoglobin reduces the oxygen-carrying capacity of the blood, which can cause tissue hypoxia (oxygen deficiency).
- Under chronic exposure (e.g., cigarette smoking), the body compensates somewhat by increasing the concentration of red blood cells and the total amount of hemoglobin available for oxygen transport.
- The central nervous system and cardiovascular system are most sensitive to CO-induced hypoxia.
- Health effects related to hypoxia of the central nervous system include loss of alertness and impaired perception, loss of normal dexterity, reduced learning ability, sleep disruption, drowsiness, confusion, and, at very high concentrations, coma.

- Health effects related to hypoxia of the cardiovascular system include decrease in exercise time to produce angina pectoris, (chest pain), increase in incidence of myocardosis (degeneration of heart muscle), and in general, increased probability of heart failure among susceptible individuals.
- Population groups at special risk of the detrimental effects of CO exposure include fetuses, persons with existing health impairments (especially heart disease), persons under the influence of drugs, and persons not adapted to high altitude who are exposed to both CO and high altitude.

The two determining factors of CO health effects are CO concentration and duration of exposure to that concentration.

Particles

Suspended particles are solid or liquid substances typically ranging in size from about 0.01 to 20 micrometers. Respirable suspended particles (RSP) generally refer to those less than 10 micrometers in diameter. Particles less than 2.5 micrometers in diameter are most damaging to health.

Particles are highly variable with respect to size, shape, and composition. All of these factors are important in determining health effects. Most larger particles are filtered out by the nose and pharynx; smaller inhalable particles can be deposited along the respiratory tract and respirable particles penetrate to the lungs.

In general, indoor concentrations of RSP will be close to outdoor concentrations except when strong particle sources are emitting indoors. For example, cigarettes emit approximately 40 milligram of RSP per cigarette, and the emission rate and resulting RSP concentration indoors depend on the number of cigarettes smoked indoors during a day.

Particulate matter is a broad class of chemically and physically diverse substances that present a risk to health. Health effects can be attributed to:

- The free radicals and acid sulfates and nitrates normally occurring in particle mixtures that can cause irritation
- The physical characteristics of insoluble particles
- Specific chemicals in the particle mixture that can be toxic or cause cancer.

The major health effects of concern that are attributed to particle exposure are:

- Impairment of respiratory mechanics--responses of respiratory mechanisms to particle exposure can range from mild temporary changes of little direct health significance to incapacitating impairment of breathing.
- Aggravation of existing respiratory and cardiovascular disease--particle-induced bronchoconstriction, mucus secretion, and other effects can aggravate bronchitis, emphysema, pneumonia, asthma, and influenza, and increase risk of heart failure from poor lung function.
- Altered host defense mechanisms--the body has mechanisms for clearing the lungs of particles, and reductions in these mechanisms increase risk of infection.
- Morphological damage--long-term exposure of animals to acid particles can produce some symptoms similar to early stages of emphysema. Insoluble particles can accumulate in the lungs and produce pneumoconiosis.
- Cancer--since all carcinogens are generally assumed not to have a threshold below which they have no effect, the carcinogenic characteristics of particles are assumed to be directly proportional to accumulated exposure.
- Mortality--mortality from exposure to particulate pollution is attributable to increased susceptibility to infectious diseases and increased risk of heart failure from inadequate oxygenation of heart muscles because of impaired lung function.

Populations especially sensitive to the harmful effects of particle exposure include: people with chronic obstructive lung disease, cardiovascular diseases, or influenza, asthmatics, children and the elderly, smokers, and persons who routinely breathe through the mouth.

CONTROL MEASURES FOR HOMEOWNERS

Control measures for indoor air quality in homes usually take the form of maximizing factors which tend to improve indoor air quality, while minimizing factors which are detrimental. In most cases, factors such as the volume of a home or ambient air quality are not under the control of a homeowner. The most commonly performed indoor air pollution control options fall into three categories:

- Increasing the air exchange (ventilation) rate of the house
- Lowering the overall emissions (source strength) of combustion sources in the home by modifying, eliminating, or changing the usage patterns of combustion sources
- Installing air cleaning devices.

A number of simple steps can be taken which will help to reduce pollutant levels in many cases. These include:

- Proper usage of appliances--combustion sources such as gas ovens and gas ranges are not designed to be used for heating purposes, and open fireplaces are of dubious value as heating sources. Kerosene or gas-fired space heaters should be operated in well-ventilated areas. This is particularly true in poorly insulated homes where they tend to operate for much longer periods of time.
- Use of spot ventilation--when they are installed and maintained properly, range hoods that are vented to the outdoors (as opposed to those which merely recirculate range exhaust) can be highly effective in preventing pollutants from reaching the indoor air environment.
- Improved maintenance of appliances--pollutant emissions from a given appliance often increase dramatically if it is allowed to reach a condition of poor tune. Usually, very poor tuning can be visually determined either by observation of increased particulate emissions (smoke) or by inspection of the flame size and color.
- Use of non-polluting sources--in many cases, functional alternatives to combustion sources exist. An important example of this option is the replacement of gas-fired range pilots with electronic spark ignition.
- Selection of make and model of appliance--classes of combustion sources such as kerosene heaters have been found to exhibit widely ranging emission rates due to such factors as design and brand, with the newer designs and certain brands often much better than others. The selection of combustion sources should take into account the likely emissions from such sources. This is particularly true of wood heaters, with the more recent airtight designs offering substantial benefits in energy efficiency and low pollutant emissions over the older, non-airtight designs. A number of widely distributed consumer-oriented publications, usually available at public libraries, perform tests on and report emission rate information for specific brands and types of combustion sources.
- Assessing the impact of reduced infiltration prior to weatherizing the home--when the air exchange rate is reduced, pollutants will generally accumulate to higher levels than before. The impact of home weatherization on indoor air quality should be taken into consideration by the homeowner in deciding upon the extent of such efforts.

- Enhancing pollutant removal through filtration--high-efficiency carbon filters can be highly effective in removing particles and, to a lesser extent, NO_2 from the indoor air. These filters can often be incorporated easily into the existing home heating, ventilation, and air-conditioning system, and they are also effective in removing some other contaminants from the air.

Table 9-1 provides summary information on the effectiveness and cost of control measures. Note that while ventilation and source removal are effective in reducing NO_2 , CO, and RSP concentrations, air cleaning is only effective for removing RSP, and, to a lesser extent, NO_2 from the indoor air. Also presented in Table 9-1 are estimated ranges of initial purchase or installation cost and operating cost. Generally, the operating costs reflect the electricity to run the devices and/or the energy needed to heat or cool the additional outdoor air used for ventilation.

TABLE 9-1. EVALUATION OF CONTROL MEASURES

EFFECT			APPROXIMATE COST	
CONTROL CATEGORY	CONTROL MEASURE	EMISSIONS	AIR EXCHANGE	OPERATING (WASHINGTON D.C.)
Ventilation	Open windows (2 windows opened 3", open continuously)	--	3/4 air changes/hr increase for 8,000 ft ³ house	\$90 - \$180 per year
	Vented range hood (100 cfm for 1.5 hr per day)	Effectively reduces NO ₂ and CO emissions from range by 70%	--	\$8 - \$14 per year
	Air-to-air heat exchanger for whole house ventilation (100 cfm at 70% heat recovery running continuously)	--	3/4 air changes/hr for 8,000 ft ³ house	\$45 - \$75 per year
Eliminating or modifying source	Eliminating source (Appliances or Tobacco smoking)	Eliminates emission	--	Difference in operating cost between "polluting" source i.e., electric and replacement range
Air cleaning (high efficiency particulate air HEPA filters)	Whole house air cleaner (65% removal efficiency for particles greater than 1 micron)	65-80% reduction in concentration	--	\$225 + installation \$26 per year for replacement filter
Air cleaning (electrostatic air cleaners with pre-filters)	Whole house air cleaner (efficiency approximately 80% using atmospheric dust and ASHRAE Standard 52-68 ^a)	70-85% reduction in concentration	--	\$250 + installation \$3.50 per year

^a American Society of Heating, Refrigerating, and Air Conditioning Engineers.

Source: EA Mueller, Baltimore, Maryland.

APPENDIX A
COMMERCIALLY AVAILABLE SAMPLING EQUIPMENT FOR
INDOOR AIR POLLUTANTS

COMMERCIALLY AVAILABLE SAMPLING EQUIPMENT FOR INDOOR AIR POLLUTANTS

Pollutant Sampler	Manufacturing Company	Sensitivity and Integrating Time	Approximate Cost
Organic vapors	Industrial Scientific Corporation 355 Steubenville Pike Oakdale, PA 15071 (412) 758-4353		
Organic vapors: hydrocarbon chemical reaction tubes	National Draeger Inc. P.O. Box 120 Pittsburgh, PA 15230 (412) 787-8383	100 to 3,000 ppm for 4 to 8 hr	\$3/tube, \$900 for pump and accessories
Organic vapors: charcoal badges	3M Corporation Technical Service Dept. 3M Center St. Paul, MN 55144 (612) 733-1110	Depends on vapors and sampling times; minimum level, 10/mg	\$10/badge; \$50 to \$300 analysis by GC or GC/MS
Formaldehyde: diffusion tube	Air Quality Research, Inc. 901 Grayson Street Berkeley, CA 94710 (415) 644-2097	5 to 7 days	\$48/kit; includes 2 monitors, analysis, and report
Formaldehyde: pro-tek adsorption badge	E.I. duPont de Nemours & Company Applied Technical Div. P.O. Box 110 Kennett Square, PA 19348 1 (800) 344-4900	1.6 to 54 ppm/hr up to 7 days or 0.2 to 6.75 ppm/8-hr TWA	\$20/badge; \$25 to \$80 for analysis
Formaldehyde: diffusion monitor	3M Corporation Technical Service Dept. Building 260-3-2 3M Center St. Paul, MN 55144 (612) 733-1110	0.1 ppm for 8 hr	\$37/monitor and analysis
NO ₂ : personal and alarm	MDA Scientific 405 Barclay Blvd. Lincolnshire, IL 60069 (800) 323-2000	2 to 3 ppm; 1/3 TLV electrochemical cell-based 15 min to 8 hr TWA	\$800/detector; \$100/output; \$2,075/dosimeter; \$1,045/readout unit
NO ₂ : diffusion tubes	Environmental Sciences and Physiology Harvard School of Public Health 665 Huntington Avenue Boston, MA 02115 (617) 732-1000	500 ppb/hr integrated	\$10/tube, research only
NO ₂ : diffusion badge	Environmental Sciences and Physiology Harvard School of Public Health 665 Huntington Avenue Boston, MA 02115 (617) 732-1000	50 ppb/hr	\$15/badge, research only

COMMERCIALLY AVAILABLE SAMPLING EQUIPMENT FOR INDOOR AIR POLLUTANTS (CONT.)

Pollutant Sampler	Manufacturing Company	Sensitivity and Integrating Time	Approximate Cost
CO: passive badge	Lab Safety Supply Co. P.O. Box 1368 Jamestown, WI 53547 (608) 754-2345	50 ppm for 8 hr produces color change	\$3/holder; \$12.75/10 indicating papers
CO: detector tube integrated	National Draeger Inc. P.O. Box 120 Pittsburgh, PA 15230 (412) 787-8383	2.5 ppm for 8 hr	\$255 pump and accessories; \$3/tube
CO: detector tube grab	Sensidyne Inc. 12345 Sparkey Road Suite E Largo, FL 33543 (813) 530-3602	5 ppm/min	\$130/pump; \$2/tube

Source: Samet, J.M., et al., "Health Effects and Sources of Indoor Air Pollution," Am. Rev. Respir. Dis., Vol. 137, pp. 221-242, 1988.

MONITORING EQUIPMENT FOR PARTICULATES FOR INDOOR QUALITY STUDIES^a

INSTRUMENT METHOD	MANUFACTURING COMPANY	FLOW RATE OR SENSITIVITY	APPROXIMATE COST
Integrated gravimetric; particles <3.5 μm diameter	Cyclone separators with filter Several manufacturers cyclones, filters, and pumps	1.7 liters/min	Pumps \$200 to \$700; filters \$2; cyclones \$20 to \$100
Integrated gravimetric; particles between 10 and 3 μm and less than 3 μm diameter	National Bureau of Standards under EPA Contract Research Triangle Park, NC 27711 (919) 541-2350	6 liters/min Separates using filters in series Batteries	Unknown
Integrated gravimetric; particles <10 μm or <2.5 μm diameter	Harvard Impactor Environmental Sciences Harvard School of Public Health 665 Huntington Avenue Boston, MA 02115 (617) 732-1000	4 liters/min Mass flow controller for 14-day timer, double impactor for sharp cut; fixed location	\$2,500
Instantaneous (2/10 sec); TSP or RSP; 0.1 to 10 μ forward light scattering	GCA-Mini-Ram (personal aerosol monitor) GCA Corporation 213 Burlington Road Bedford, MA 01730 (617) 275-5444		
Semi-instantaneous; RSP	Piezobalance (Model 3500) TSI Inc. P.O. Box 64394 St. Paul, MN 55164 (612) 483-0900	>10 $\mu\text{g}/\text{m}^3$ 2-min average depending upon concentration	\$3,000 to \$5,000
Continuous; RSP submicron light-scattering multi-sensor monitor	Handheld Aerosol Monitor (HAM) PPM Inc. 11428 Kingston Pike Knoxville, TN 37922 (615) 966-8796	>10 $\mu\text{g}/\text{m}^3$ mass concentration; 1.5 liters/sec	\$3,000 to \$10,000

^aParticles can be measured using a variety of techniques. Using cyclone or impactor separators, smaller size fractions can be collected on filters. Mass can also be measured using the optical properties of particles. For the most part, measuring particles requires equipment costing several hundred to a few thousand dollars. Equipment using filters require that they be preweighted and postweighted in a temperature- and humidity-controlled room.

Source: Samet, J.M., et al., "Health Effects and Sources of Indoor Air Pollution," Am. Rev. Respir. Dis., Vol. 137, pp. 221-242, 1988.

APPENDIX B

A PROCEDURE FOR ESTIMATING INDOOR NO₂ CONCENTRATIONS

This section presents a method for estimating peak NO₂ levels in a given home. Although this method is an approximation only and may not be accurate in some cases, it is provided as an illustration of how models can be used to make predictions of indoor pollutant levels.

Peak NO₂ concentrations often occur in a home when sources which emit NO₂ for only short periods of time (such as gas ranges and ovens) are operated concurrently with longer term sources, such as kerosene heaters. Since these short-term sources are typically operated for periods of one to three hours, their contribution to the daily average NO₂ concentration may be less important than their effect on peak levels.

In order to estimate peak indoor NO₂ concentrations for a given home, reasonable approximations of the pollutant source strength, house volume, and house air exchange rate must first be inferred. Techniques for estimating these values are provided below.

SOURCE STRENGTH

The NO₂ source strength within a home is a function of the emission rate of each appliance and the length of time each is used. Table B-1 can be used to estimate the source emission rate for NO₂ from certain common appliances located within the home. To use these tables, fill in the number of units of each particular source which may be concurrently operating within the home at any given time frame. Also, fill in the length of time, in hours, each appliance is operated. Multiply these numbers by the corresponding NO₂ emission rate for each appliance to estimate the source strengths for each appliance. The total pollutant source strength is the sum of the emissions from each appliance.

The appliances listed in Table B-1 and the emission rates designated for each are considered representative of the important NO₂ sources which may exist within a given home under reasonable conditions. Gas appliances such as water heaters, clothes dryers, and the like are usually intended to be vented to the outdoor air and are not considered as important sources. Also, the values presented assume properly operated and maintained equipment. This means, for instance, that a gas range is clean and mixture settings have not been tampered with, or that a kerosene heater is operated in a room of appropriate size as specified in the manufacturer's instructions. Figure B-1 illustrates the range of values that have been reported for emission rates for NO₂ for the different sources and the location of the rates used in this procedure within that range.

HOUSE VOLUME

Home volume is equal to the length of the home multiplied by the width multiplied by the height of the rooms inside. For example, if your home measures 30 feet by 50 feet and has 8-foot high ceilings, your home volume equals $30 \times 50 \times 8 = 12,000$ cubic feet. If your home has the same measurements as this but is two stories high, the volume equals $12,000 \times 2 = 24,000$ cubic feet. When estimating the volume of a home, the volume of the basement is usually not

TABLE B-1. PROCEDURE FOR ESTIMATING NO₂ EMISSIONS

SOURCE	NUMBER OF UNITS	X	USAGE RATE	X	RATE (MG/HR)	SOURCE STRENGTH
Gas Range:						
Oven	_____	X	85	X	_____	_____
Top Burners	_____	X	170	X	_____	_____
Unvented Gas Space Heater	_____	X	560	X	_____	_____
Kerosene Heater:						
Convective	_____	X	130	X	_____	_____
Radiant	_____	X	35	X	_____	_____
TOTAL					_____	_____

● Emission rate used in estimating procedure

Figure B-1. Comparison of Range of NO₂ Emission Rates Reported in Literature for Various Combustion Sources to Emission Rates Used in Estimating Procedure

considered unless it either contains combustion appliances, is configured to permit free flow of air between the basement and the rest of the house, or a forced-air system mixes the basement air with that of the rest of the home. The same considerations also apply to attached garages.

AIR EXCHANGE RATE

Air exchange rates are difficult to determine even under controlled test conditions. For this section, average home air exchange rates have been estimated as high, medium, or low, based on building characteristics such as energy conservation measures. Table B-2 is a rough guide for estimating the air exchange rate for a particular home.

ESTIMATING THE PEAK NO₂ CONCENTRATION FOR YOUR HOME

Once the source emission rate, home volume, and air exchange rate have been estimated, peak indoor NO₂ concentrations can be estimated using the graphs in Figures B-2 and B-3. These figures provide estimates for peak one-hour and three-hour exposures. The first step is to find your source strength value on the horizontal axis of the figure you choose to use. Then, locate the value for the air exchange rate on the vertical axis. In order to determine the estimate for the peak NO₂ concentration in your home, draw a perpendicular line upwards from the point on the horizontal axis, and then draw a perpendicular line to the right from the point on the vertical axis. The peak NO₂ concentration curve nearest to the intersection of these two lines is the resulting estimate for a home 8,000 cubic feet in volume. If your home is more or less than this volume, see the first point listed below.

Two Important Points

- The graphs were developed based on house volumes of 8,000 cubic feet. If your home volume is greater than this, multiply the concentration which you just calculated by 8,000/your volume. For example, if your home volume is 14,000 cubic feet and the estimated concentration from the charts is 0.7 ppm, the actual adjusted concentration is:

$$\frac{8,000}{14,000} \times 0.7 = 0.4 \text{ ppm}$$

- For the calculations described here, outdoor pollutant concentrations were assumed to be the national average (0.015 ppm or 28 µg/m³). If you live in an urban area with significantly higher outdoor concentrations than the national averages, you should note that your calculations may be underestimating indoor pollutant levels. Of course, the converse is true if you live in areas with significantly lower outdoor concentrations.

TABLE B-2. HOME AIR INFILTRATION FROM OUTDOORS

CHARACTERISTICS	AIR EXCHANGE RATE	
	RANGE	TYPICAL VALUE
Energy conservation design (within last 10 yrs); tight construction, weatherstripping, storm doors and windows, caulking; never feels drafts from outdoors.	"Low" Less than 0.4/hr	0.3/hr
Structure using modern day building materials; sheetrock interior walls, double hung windows or equivalent caulking and storm sash applied to heated spaces; some drafts felt on windy days; approximate home age may be between 10 and 50 years.	"Medium" 0.4 - 1.1/hr	0.75/hr
Older structures possibly containing lath and plaster walls, rough hewn beams, little or no caulking; light may be seen through cracks in exterior walls (around windows and doors); draperies often move due to drafts from wind outdoors; approximate house age may be 50 or more years.	"High" Greater than 1.1/hr	1.2/hr

Figure B-2. Results of Mathematical Model for Peak Indoor Concentration of NO_2 Assuming Constant Emissions for One Hour for Volume Equal to 8,000 Cubic Feet

Figure B-3. Results of Mathematical Model for Peak Concentration of NO_2 Assuming Constant Emissions for Three Hours for Volume Equal to 8,000 Cubic Feet

MATHEMATICAL BASIS FOR ESTIMATING NO₂ CONCENTRATIONS

The central elements of the estimating procedures presented above are the "constant concentration" curves plotted against emission rate on the horizontal axis and air exchange rate on the vertical axis. The constant concentration curves were developed for NO₂ to reflect the fact that the health effects of this pollutant is more strongly determined by peak concentrations. Figure B-4 illustrates a plot of concentration versus time developed by the following mathematical model for NO₂.

Equation B-1 below, previously described in Section 5, was used as the basis for estimating indoor air pollutant concentrations of NO₂.

$$C_i(t) = \frac{PAC_o + S/V}{A+R} (1 - e^{-(A+R)t}) + C_i(0)e^{-(A+R)t} \quad (B-1)$$

Where:

- C_i = indoor contaminant concentration at time "t" (μg/m³)
- C_o = outdoor contaminant concentration (μg/m³)
- P = fraction of outdoor contaminants that penetrate the building shell (1 = 100% penetration)
- A = air exchange rate in air changes per hour (ACH) (hr⁻¹)
- S = generation rate of indoor contaminants, also called source strength (μg/hr)
- V = volume of the indoor space
- R = net rate of removal processes other than air flow (1/hr)

To generate curves of concentration as a function of air change rate and emission rate, this equation was rearranged and solved for the source emission rate, S, as shown in equation B-2 below. This equation was used to plot lines of constant concentration by varying air change rate and emission rate over the ranges indicated on the graphs. All other parameters were held constant. Table B-3 lists the parameters and assumed values used during the above procedure.

$$S = \frac{(A+R)[C_i(t) - C_o e^{-(A+R)t}]}{1 - e^{-(A+R)t}} - PAC_o \quad (B-2)$$

Figure B-4. NO₂ Concentrations Resulting from a Source Operating for 1 Hour

TABLE B-3. PARAMETERS USED TO GENERATE NO₂ CONCENTRATION CURVES

PARAMETER	NO ₂
C_o	0.015 ppm
$C_i(0)$	0.01 ppm
V	227 m ³
R	0.15 hr ⁻¹
P	1.0

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APPENDIX C

GLOSSARY

ABSORPTION - The dissolving of one or more soluble components of a gas mixture in a liquid. This may be a physical phenomenon or may involve solution of the material in the liquid followed by reaction with one or more constituents in the liquid solution.

ACCEPTABLE AIR QUALITY - Air in which there are no contaminants at concentrations known to be harmful and with which a substantial majority (usually 80 percent) of the people exposed do not express dissatisfaction.

ACUTE - Short-term, severe, as contrasted with chronic.

ADSORPTION - Process by which ions or molecules present in one phase condense and concentrate on the surface of another phase. Three types: physical, chemical, and exchange adsorption, depending on the forces acting between the surface and the material being concentrated.

AEROSOLS - Fine solid or liquid particles suspended in air.

AIR CLEANER - A device used to remove airborne impurities such as dusts, gases, vapors, fumes, and smoke.

AIR CONDITIONING - The process of treating air by controlling its temperature, humidity, cleanliness, and distribution.

AIR EXCHANGE - Movement of air into and out of a building by infiltration, exfiltration, natural ventilation, and mechanical ventilation.

AIR EXCHANGE RATE - Amount of air that flows into or out of a building in a specified amount of time (usually expressed as "air changes per hour" or "ach").

AIRWAY REACTIVITY - Sensitivity of the inner passages to flow of air caused by decreased diameter of airways from inflammation, mucous blockage, or collapse.

AMBIENT AIR - That portion of the atmosphere, external to buildings, to which the general public has access.

ANGINA PECTORIS - Chest pains caused by inadequate oxygenation of heart muscles. Pains and other symptoms last for a few seconds to several minutes.

AROMATIC HYDROCARBONS - Hydrocarbons containing benzene rings.

ASTHMA - Bronchial spasms characterized by difficulty in breathing, wheezing and tightness of the chest.

BENZO-[A]-PYRENE (BaP) - A tarry, organic material composed of five aromatic rings. BaP has shown to induce cancer in animals.

BRONCHIECTASIS - Destruction of the supporting elastic and muscular components of bronchial walls following severe lung infections.

BRONCHITIS - Inflammation of bronchial mucous membranes of the lungs, with excessive mucous production.

BRONCHOCONSTRICTION - Constriction of the bronchial tubes (large airways) in the lungs.

CAPILLARY - A minute blood vessel.

CARBON MONOXIDE - Colorless, odorless gas that is a product of incomplete combustion of gas, oil, wood, coal, and other fuels.

CARBOXYHEMOGLOBIN - Hemoglobin in which the oxygen-binding site is blocked by carbon monoxide, thus destroying its ability to bind and carry oxygen.

CARCINOGENIC - Cancer causing.

CARCINOMA - A type of cancer of the cells of the skin and internal membranes.

CARDIOPULMONARY - Related to the heart and lungs.

CATION - A positively charged ion.

CHAMBER STUDY - Research conducted using a closed vessel in which pollutants are reacted or substances exposed to pollutants.

CHRONIC - Longstanding, repeated, as contrasted with acute.

CILIA - Small hair-like organelles which, in the lungs, move mucous and absorbed particles upward to the esophagus where they are swallowed. They are part of the lung's defense system against inhaled particles, including bacteria.

COMBUSTION AIR - Air that is used in the burning of wood, oil, coal, and other inflammable substances.

COMBUSTION APPLIANCE - A fuel-burning (oil, gas, coal, or wood) device such as a range, furnace, or water heater.

CONCENTRATION - The quantity of one constituent dispersed in a defined amount of another; for example, lb per ft³, kg/kg, or parts per million (ppm).

CONTAMINANT - Any airborne constituent that reduces the quality of the air.

CONVECTION - Movement of fluids (gases and liquids) in response to differences in density caused by temperature differences.

CORRELATION - Co-relation, a statistical measure of the extent to which two phenomena move in concert, either together (positive correlation) or opposite (negative correlation).

CRITERIA POLLUTANT - EPA has set standards for the following pollutants in outdoor air: nitrogen dioxide, sulfur dioxide, ozone, lead, carbon monoxide, and total suspended particulates.

CUTANEOUS VASCULATURE - blood vessels of the skin.

DEPOSITION - Particles settle out of the air.

DIFFUSION - Spontaneous scattering of particles and molecules from areas of high concentration to areas of low concentration.

DISPERSION - Movement of contaminants by diffusion and mixing.

DOSE - Amount times time of exposure to a biological stimulus, usually chemical.

DOSE-RESPONSE RELATIONSHIP - A quantitative relationship between exposure (magnitude and time) to a biologically active chemical or other stimulus and the biological effects of the exposure.

DYSPNEA - Labored or difficult breathing, often accompanied by pain.

EFFICIENCY - Effectiveness of a device, usually expressed as percent of maximum effectiveness.

ELECTROSTATIC PRECIPITATION - Removal of particles from the air by attraction to charged materials.

EMISSION RATE - Amount of contaminant released into the air by a source in a specified amount of time.

EMPHYSEMA - Enlargement of the small air sacs of the lung with loss of elasticity caused by destruction of tissues from exposure to pollution.

ENDOGENOUS - Produced inside the body.

EPIDEMIOLOGY - A branch of science that deals with statistical analysis of relationships between incidences and distributions of diseases and distributions of possible causes. Epidemiological studies use statistics to shed light on the causes of diseases, and the relative contributions of different causes.

EXFILTRATION - Uncontrolled movement of air out of a building through cracks and interstices in the building envelope.

FILTRATION - Removal of particles from the air by passing the air through a material that screens them out.

FORMALDEHYDE (HCHO) - A colorless, gaseous compound, used in the manufacture of resins and dyes, and as a preservative and disinfectant. Present in many synthetic materials and produced in small amounts during combustion.

FREE RADICALS - Molecules having one unpaired electron making them highly reactive.

GI TRACT - Gastro-intestinal tract, the gut.

HALFTIME - Time required for concentration to be reduced by one half.

HEAT EXCHANGER - A device in which heat is transferred from one air stream to another.

HEMATOLOGICAL - Related to the blood and blood-forming organs.

HEMOGLOBIN - The red pigment in blood that binds oxygen and carries it from the lungs throughout the body.

HYGROSCOPIC - Water seeking.

HYPER-REACTIVE - Unusually sensitive to irritants.

HYPOXIA - Low oxygen content in the blood.

INDEX - A measure used to estimate the magnitude of some other, usually unknown or unmeasurable phenomenon. One kind of pollution is often used as an indicator (index) of total pollution exposure.

INFILTRATION - Uncontrolled movement of air into a building through cracks and interstices in the building envelope.

INHALABLE PARTICLES - Particles that are not filtered out by the nose and pharynx and that are deposited along the respiratory tract; upper size limit is approximately 10 microns.

IONS - Molecules having unbalanced numbers of electrons and protons, making them electrically charged.

LESION - A wound or injury.

LUNG DEFENSE MECHANISMS - In the lungs, mechanisms which remove potentially harmful substances particularly removal of particles by ciliary action and engulfment by macrophages.

MACROPHAGE - In the lungs, cells which are able to move about and engulf particles. They are part of the lungs defense system against inhaled particles, including bacteria.

MASS-BALANCE APPROACH - A method of studying the change in concentrations of contaminants in the air by measuring rates of contaminant emission and removal.

MECHANICAL VENTILATION - Forced movement of air by fans into and out of a building.

METHEMOGLOBIN - Hemoglobin in which the oxygen-binding site is blocked by a methyl group, thus destroying its ability to bind and carry oxygen.

MICRON - Unit of length equal to one thousandth of a millimeter or forty millionths of an inch.

MIXING - Distribution of particles and molecules by movement of air volumes.

MORPHOLOGICAL - Structural.

MYOCARDOSIS - Any noninflammatory degeneration of heart muscle.

NATURAL VENTILATION - Movement of air into and out of a building through intentionally provided openings, such as windows or doors, or through infiltration.

NITRATES - Reaction products of metals or organic compounds with nitric acid.

NITRIC OXIDE (NO) - A colorless gas formed during combustion that is highly irritating to the skin, eyes, and respiratory tract.

NITROGEN DIOXIDE (NO₂) - A reddish-brown gas formed during combustion that is highly irritating and damaging to the respiratory tract.

NITROGEN OXIDES - Several compounds, including nitric oxide and nitrogen dioxide, that are formed during combustion of gas, oil, wood, and other fuels; sometimes abbreviated NO_x.

ORGANIC COMPOUNDS - Substances that contain carbon and hydrogen.

PEROXYACETYLNITRATES - Complex organic molecules that are strong eye irritants in smog.

PHARYNX - The portion of the throat between the cavity of the mouth and the esophagus.

PHOTOCHEMICAL - Chemical reactions promoted by sunlight, as in smog formation.

PNEUMOCONIOSIS - A degenerative condition of the lung caused by inhalation of dust, fumes, vapors, or gases.

POLYCYCLIC AROMATIC HYDROCARBONS - A class of complex organic molecules commonly produced during combustion. They are known carcinogens in animals and assumed to be carcinogenic in man.

REMOVAL MECHANISM - Object or process that removes contaminants from a media, such as air or water.

REMOVAL RATE - Amount of contaminant removed by a removal mechanism per unit time.

RESPIRABLE PARTICLES - Particles that penetrate to the lungs when inhaled; upper size limit is approximately 5 microns.

RESPIRATORY EPITHELIUM - The membrane lining of the lungs.

SMOKE - Mixture of gases and small particles generated by incomplete combustion.

SULFATES - Reaction products of metals or organic compounds with sulfuric acid.

SUSPENDED PARTICLES - Particles so small that they remain in the air and settle out only slowly under the force of gravity; upper size limit is approximately 100 microns.

SYNERGISTIC - A situation in which effective results of two or more simultaneous actions is greater than the sum of their individual effects.

SYSTEMIC - Related to the whole body rather than one of its parts.

TOTAL SUSPENDED PARTICLES - The weight of particles suspended in a unit of volume of air when collected by a high volume air sampler.

TOXIC - Poisonous.

TRAUMA - Physical damage to tissues.

VAPOR - Gaseous phase of a substance that is predominantly liquid at room temperature and standard pressure.

VENTILATION - The process of supplying and removing air by natural or mechanical means to and from any space.

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