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POTENTIAL HEALTH EFFECTS OF RESIDENTIAL ENERGY CONSERVATION MEASURES

FINAL REPORT

(February 1980 - February 1981)

Prepared by

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ADL Reference 84572

For

Gas Research Institute
Contract No. 5014-360-0286

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GRI Project Manager

Donald O. Johnson

Environment, Safety and Distribution Division

July 1981

RESEARCH SUMMARY

TITLE	Potential Health Effects of Residential Energy Conservation Measures GRI Code: GRI 79/0097 GRI Contract Number: 5014-360-0286
CONTRACTOR	Arthur D. Little, Inc. Acorn Park Cambridge, MA 02140
PRINCIPAL INVESTIGATOR	G. Stewart Young
TIME SPAN	February 1980 to February 1981
MAJOR ACHIEVEMENTS	The major achievement of this study was the collection, review, and critical discussion of information pertaining to indoor air quality, particularly the impact of current and future energy conservation measures; i.e., reducing residential air infiltration, on the levels of pollutants found in the residential environment. Controversial issues and areas where knowledge is lacking were identified and formed the basis for developing recommendations for future research and development activities.
RECOMMENDATIONS	Future research should include the quantitative characterization of personal exposure to oxides of nitrogen in the residential environment distinguishing quantitatively between exposure to nitric oxide and nitrogen dioxide. Some research suggests that nitric oxide may be much less harmful than nitrogen dioxide at levels found in the indoor environment. Once characterized, it will be necessary to determine the complete burden of pollutant exposure, to determine whether there are health effects associated with these exposures, and to distinguish between responses which are adaptive or protective in nature and responses which reflect pathological changes. Because of the significance attached to the results of experimental human exposure studies, GRI should monitor all research in this area and study results should be subjected to critical review.Reviews should

determine the validity of the exposure and response measurements and the relationship between the response and any actual or potential adverse health effect. If the actual types of personal exposures experienced in the indoor environment seem to be associated with adverse health effects, epidemiological research will be required to resolve the issue.

Research related to instrumentation for monitoring oxides of nitrogen and evaluating peak exposures is also a high priority while the need for control technology research will depend upon the levels of risk identified in research related to health effects. Other specific research needs include more complete characterization of pollutant emissions and quantification of source strengths both in the laboratory and in the residential environment. Research should address not only oxides of nitrogen and carbon monoxide but also organics and radon. The contribution of tobacco smoking to indoor pollutant levels also deserves further research.

DESCRIPTION OF WORK COMPLETED

Literature search and data collection activities focused on the identification of types, sources, and concentrations of pollutants found in the residential environment; epidemiological studies of the health effects of indoor air pollution; domestic and foreign standards for pollutants found in the residential environment; and studies which characterize and measure rates of residential air infiltration. The literature was reviewed and annotated bibliographies were prepared for indoor air quality, indoor air pollution health effects, and residential air infiltration.

Topical discussions which focused on the current status of indoor air quality and the health effects of exposure to indoor air pollutants were prepared. These discussions conclude that the epidemiological evidence is inconclusive regarding the effects of indoor air pollution on residential populations. The need for special concern regarding sensitive populations is also uncertain because the response measured in experimental exposure studies may be an adaptive response rather than a pathological change.

Air infiltration data were analyzed and it was found that individual homes vary considerably in terms of their air exchange rate. Factors related to the house itself, the behavior of residents, and the microenvironment surrounding the house were identified and their complex relationship was described. An estimation of future trends of infiltration rates suggested that some houses, primarily those with the greatest rates of infiltration, will be tightened. Concurrently, increasing awareness that very low air exchange rates may result in indoor air quality problems will tend to limit the extent of these reductions. Investigation of the relationship between indoor and outdoor pollutants and their relative contributions to indoor air quality resulted in the construction of a matrix which combines the indoor-outdoor relationships with changes in infiltration rates and different types of pollutants. The complexity of the issue was demonstrated and a number of research questions were developed to delineate what must be known to resolve the problem. Finally, recommendations for future research and development concerning indoor air quality were developed.

GRI COMMENT

The purpose of this project was to review critically existing literature on indoor air quality to identify the types, levels, and sources, and health effects of the major pollutants found in the home. In addition, the study reviewed the literature on air infiltration, noting the trends in this area and evaluating the effect these trends might have on indoor air quality. The information obtained from this project is being incorporated into GRI's five-year Environmental Research Plan for Gas Utilization Technologies, and will serve as the basis for further research in this area.

GRI accepts the contractor's recommendations and will be implementing some of them in 1981.

ACKNOWLEDGEMENT

Major participants in this study were Mr. John H. Hagopian, Mr. E. Robinson Hoyle, Dr. Cathy Campbell, and Dr. Robert P. Wilson. Their contributions are gratefully appreciated as are the comments and direction provided by Dr. Donald O. Johnson, Manager of Environmental Research at the Gas Research Institute, and the GRI Environmental Advisory Group.

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EXECUTIVE SUMMARY

1. INTRODUCTION

In response to recent concerns about the quality of air in the residential environment and the potential adverse impact of energy conservation measures on indoor air quality and the health of the residential population, the Gas Research Institute (GRI) sponsored a study which involved the collection and review of literature related to indoor air quality and energy conservation. The underlying objective of the study was to assess the potential impacts or risks which reduced rates of air infiltration may pose for the residential population. The final report of this study consists of specific chapters which address indoor air quality, the health effects of indoor air pollution, air infiltration, trends in residential air infiltration, indoor-outdoor pollutant relationships, recommendations for future research and development, and national and international standards. Annotated bibliographies for indoor air quality, health effects, and air infiltration are presented as appendices.

2. INDOOR AIR QUALITY

Current approaches for characterizing indoor air quality evolved from techniques applied in the ambient outdoor environment such as 24-hour continuous area sampling. Other approaches such as personal and area monitoring were developed primarily in the occupational or industrial environment. The majority of indoor air sampling has been performed with environmental techniques employing area monitoring of the entire residence. Recently, studies have integrated personal sampling into the indoor air sampling methodology.

In general, gaseous pollutants measured in indoor environments include carbon monoxide (CO), nitrogen dioxide (NO_2), nitric oxide (NO), sulfur dioxide (SO_2), carbon dioxide (CO_2), ozone (O_3), ammonia (NH_3), and formaldehyde (HCHO). Additional gaseous pollutants which have been measured in the residential environment are total non-methane hydrocarbons (including fluorocarbons) and a wide variety of organics (various solvents and vinyl chloride). Particulate pollutants include the total suspended particulate (TSP), respirable suspended particulate (RSP), lead (Pb), water-soluble sulfates ($SO_4^{=}$) and nitrates (NO_3^-), smoke, and radon daughters attached to particulates. Table 1 shows that the sources of these pollutants are numerous and include heating systems, cooking appliances, building construction materials, consumer products, and human activities (smoking, etc.).

Numerous studies have been conducted to quantify the levels of pollutants in the residential environment, however, most of these studies suffer from some sort of methodological or technical problem, the most essential being the inability to correlate measured concentrations with actual exposures to residents. In order to overcome some of these difficulties, the Harvard Six City Study is employing a unique sampling

TABLE 1

EXAMPLES OF INDOOR AIR POLLUTION IN RESIDENTIAL BUILDINGS

Sources	Pollutant Types
OUTDOOR	
Ambient Air	SO_2, NO, NO_2, O_3, Hydrocarbons, CO, Particulates
Motor Vehicles	CO, Pb
INDOOR	
Building Construction Materials:	
Concrete, Stone	Radon
Particleboard	Formaldehyde
Insulation	Formaldehyde, Fiberglass
Fire Retardant	Asbestos
Adhesives	Organics
Paint	Mercury, Organics
Building Contents:	
Fossil Fuel Combustion (gas, oil, coal)	CO, SO_2, NO, NO_2, Particulates
Furnishings	Organics, Odors
Water Service, Natural Gas	Radon
Human Occupants:	
Metabolic Activity	CO_2, NH_3, Organics, Odors
Human Activities:	
Tobacco Smoke	CO, NO_2, HCN, Organics, Odors
Aerosol Spray Devices	Fluorocarbons, Vinyl Chloride
Cleaning and Cooking Products	Hydrocarbons, Odors, NH_3
Hobbies and Crafts	Organics

Source: C.D. Hollowell et al., 1979.

strategy which consists of a three-stage, aerometric monitoring system including continuous ambient monitoring at a central site, an array of indoor and outdoor satellite monitors, and personal monitoring on a limited basis. Unfortunately, it will be several years before these results are available and preliminary reports have not provided any significant personal exposure data.

3. HEALTH EFFECTS OF INDOOR AIR POLLUTION

After reviewing the scientific literature, many questions regarding the health effects of exposure to low levels of nitrogen dioxide remain unanswered. In part, this results from incomplete and conflicting epidemiological data. For example, a valid assessment of the health effects associated with exposure to nitrogen dioxide requires that all exposures to nitrogen dioxide(indoor as well as outdoor) be examined. In addition, exposures from other pollutants, which may have adverse or protective health effects, must be fully characterized. Most existing epidemiological studies, however, are restricted to a single source such as the residential or occupational environment and, therefore, the results of such studies are questionable.

Unfortunately, even the limited amount of exposure data which is collected in studies of indoor pollutant health effects suffers from fundamental problems. For example, gas cooking has been used as a surrogate measure which implies elevated indoor levels of oxides of nitrogen and, thus, implies elevated exposure. However, such a surrogate measure ignores variables such as the frequency and duration of appliance use, venting of appliances, sources and amounts of infiltration, and occupant activities which may have a considerable influence on exposures. Other problems with indoor pollutant epidemiology studies include the quality of pollutant measurements and the effect of confounding variables such as smoking or socioeconomic status on health.

Indoor epidemiology studies include the EPA-Long Island study which was a periodic survey of common respiratory ailments among gas and non-gas using households. Although significant associations were claimed, the authors cautioned that the study was based upon preliminary data. Apparently, no final results were published. Some of the most publicized and controversial studies were conducted by Melia and her colleagues in England. While the "gas cooking effect" was significant under certain circumstances, contrary results tend to diminish the credibility of the studies. For example, results were inconsistent for males and females and also for different geographic locations. Follow-up studies were also plagued by inconsistencies which led to the observation that some third factor, sporadically associated with gas cooking, might be responsible for the observed health effects. Observations by Goldstein include the speculation that the reported associations between exposure to nitrogen dioxide and respiratory disease may actually result from socioeconomic factors such as crowding and poverty. Melia has noted that failure to consider other contributory factors has led to misinterpretation of their results and has cautioned that their observations are inconsistent and not indicative of an association between NO_2 exposure and adverse health effects. Goldstein fairly describes the state of the art of indoor air pollution epidemiology when he warns, regarding the Melia studies, that the results "do not provide a definitive answer to the question of whether NO_2 is harmful to health at concentrations in the home" (see Reference 19, Chapter 3).

A study of major proportions which reports no association between gas cooking and respiratory disease is the Indoor Epidemiology Study conducted by Keller and associates. Because of methodological problems with sample selection and data collection procedures, this study does not provide very strong support for the null hypothesis. However, one could claim that the methodological problems were not severe and would not be likely to mask a strong association. Also it should be noted that the study population was not restricted to children or asthmatics and thus may be more representative of the national population.

A preliminary report from the Harvard Six Cities Study provides some evidence for a "gas stove effect," however, the results are also inconsistent. Despite the avowed importance of personal exposure sampling for the study methodology, this report relies upon the presence or absence of a gas stove as an indirect measurement of nitrogen dioxide exposure. Also, some methodological and technical problems have been identified including flaws in the sodium arsenite measurement technique and a lack of information on socioeconomic variables.

Overall, there are a variety of serious problems associated with indoor epidemiological studies. The data are limited, imprecise, and contradictory. Moreover, clinical data are not representative of actual exposures and results from animal toxicological studies are difficult to extrapolate to humans.

4. AIR INFILTRATION

According to the American Society of Heating, Refrigeration, and Air-Conditioning Engineers (ASHRAE), infiltration is "air leakage through cracks and interstices, around windows and doors, and through floors and walls, into a building; its magnitude depends on the type of construction, workmanship, and condition of the building, and (it) cannot be effectively controlled by the occupants." Infiltration is often called "air leakage" or "natural ventilation" although the latter usually refers to intentional displacement of air through specified openings such as windows, doors, and ventilators. When fans are used, the appropriate term is "mechanical ventilation." The total infiltration rate is described in terms of the "air exchange" rate with units of air changes per hour (ACPH).

One of the major problems in studying residential air infiltration is the wide variety of factors which can influence the magnitude of the infiltration rate. These factors include:

- Quality of workmanship
- Materials of construction
- Degradation of building materials
- Residential microclimate
- Leakage path characteristics
- Internal barriers to air flow
- Indoor-outdoor temperature gradients
- Home insulation quality
- Ice and snow accumulation on building exterior
- Humidity and temperature variations

Under certain circumstances, the infiltration rate can be a small part of the total residential ventilation rate such as when natural ventilation (e.g., opening windows and doors) and mechanical ventilation (e.g., attic, bathroom, and kitchen fans) systems are active. Experimental studies of residential infiltration have been conducted for the purpose of developing generalized estimation models. For example, the ASHRAE crack and air change model provides crude approximations while physical models have progressed to a stage where they show promise as a viable and accurate technique. Experimental studies also provide data on the range of residential infiltration rates. It is not uncommon to find tight homes with infiltration rates on the order of a few tenths of an air change per hour. Similarly, there are loose homes that may experience two or more air changes per hour. Individual homes may vary considerably (e.g., 0.5-1.6 ACPH) over a short time frame depending upon the circumstances. In general, infiltration rates are substantially lower in summer than in winter.

5. TRENDS IN RESIDENTIAL AIR INFILTRATION

As energy costs have continued to escalate and spot shortages have occasionally been experienced, attention has been focused on the identification and implementation of energy conservation measures. In residential housing, efforts have been directed toward the reduction of air infiltration losses. Although the trend toward reduced infiltration appears to be obvious, there is little information which can be used to quantify the trend. Specifically, data are needed to describe the current distribution of infiltration rates by housing type and other influential factors such as climate. Also, data are needed to describe which types of houses are currently being "tightened" and what effect these efforts will have on the infiltration rate and, subsequently, indoor air quality.

Overall, one would expect that the current downward trend in air infiltration rates will continue into the near future due to its "momentum." Results of current and future studies examining the relationship between health effects and reduced air infiltration may modify this trend. In the meantime, the public will be informed about indoor air quality through the news media and popular literature. Home builders may be discouraged from building tighter homes by increased awareness of potential problems and, possibly, by regulations that set forth a minimum allowable infiltration or total ventilation rate in new homes. Furthermore, increasing pressure may be brought to bear on the providers of building materials and certain appliances to reduce pollutant emission levels from their products and/or to develop effective controls.

6. INDOOR-OUTDOOR POLLUTANT RELATIONSHIPS

The concentrations of airborne contaminants at particular locations in the home are a complex function of indoor pollution source strengths, duration of source activation, air infiltration or ventilation rates, quality of infiltrating air as a function of time, and the rates (if any) of contaminant decay. The common assumption that reducing residential air infiltration rates will result in increased levels of indoor air pollution is somewhat misleading because the relationship between infiltration and indoor pollution depends upon the rate of decay of the various pollutants and the relative contribution of indoor and outdoor sources to indoor levels. Table 2 summarizes the discussion of indoor-outdoor pollutant relationships in a matrix which considers whether ventilation rates are increased or decreased and whether pollutant sources are indoors or outdoors for situations where pollutants are either conservative or non-conservative in terms of decay.

Inspection of the matrix can clarify why the entire subject area of reduced infiltration rates and indoor air quality is controversial and difficult to address in a manner that results in clear-cut solutions. Reduced ventilation rates have adverse impacts on indoor exposures and concentrations when the source is indoors, and generally beneficial impacts when the source is outdoors. Conversely, reduced rates can lead to lower energy usage and lower pollution emissions from home furnaces. Increased ventilation rates have almost an exactly <u>opposite</u> effect in <u>every</u> case.

The issues raised become substantially more complicated when one attempts to define the health impacts of ventilation rate changes in homes. Since any change may increase exposures to one set of contaminants, i.e., those generated indoors or outdoors, while decreasing exposures to another set, and since the "mixture" of contaminants generated indoors differs from the mixture generated outdoors, there are certain tradeoffs involved that are difficult to assess.

7. RECOMMENDATIONS FOR RESEARCH AND DEVELOPMENT CONCERNING INDOOR AIR QUALITY

Throughout this study, areas of controversy and lack of knowledge have been identified and, in some cases, specific research questions have been posed. As a result, it is fair to state that there is a definite need for research and development activities which focus on the issue of indoor air quality. The general research topics of interest include:

- Monitoring and Pollutant Characterization
- Instrumentation
- Health and Welfare Effects
- Risk Assessment
- Control Technology

TABLE 2

SUMMARY FINDINGS VIS-A-VIS INDOOR AIR QUALITY

Pollutant Type	Indoor Sources: Impact of Reduced Ventilation	Indoor Sources: Impact of Increased Ventilation	Outdoor Sources: Impact of Reduced Ventilation	Outdoor Sources: Impact of Increased Ventilation
Conservative*	Bad. Significant increase in exposure and concentrations.	Good. Significant decrease in exposures and concentrations.	Somewhat good. No major impact on exposures, but decreases peak concentrations experienced.	Somewhat bad. No major impact on exposures, but increased peak concentrations experienced.
Non-Conservative**	Somewhat bad. Moderate increase in exposures and concentrations, but indoor conditions may still be better than those outdoors.	Good. Moderate decrease in exposures and concentrations.	Good. Can be significant decrease in exposures and concentrations.	Somewhat bad. Can increase in exposure and concentrations, but indoor conditions may still be better than those outdoors.

* Relatively lower rates of decay (e.g., CO)

** Realtively higher rates of decay (e.g., NO_2)

SOURCE: Arthur D. Little, Inc.

While each of these topical areas is quite broad, including many research needs which are of little direct interest to the Gas Research Institute, a number of relevant research needs have been identified. For example, there are several areas such as monitoring and health effects where large-scale multi-year studies are needed. Specific research topics of interest include developing a better understanding of the emission of NO in the indoor environment and its conversion to NO_2, developing a better characterization of personal exposures to oxides of nitrogen, and reviewing experimental human exposure studies of normal and sensitive populations to determine the validity of their results. Additional research should be conducted to characterize pollutant emissions from various types of appliances under various types of operating conditions. Such research should include laboratory and field sampling and should include organics such as nitrosamines and radon as well as oxides of nitrogen and carbon monoxide. Also, research should be conducted to evaluate the relative contributions of various pollutant sources such as ambient air infiltration and tobacco smoking.

Control technology is an area where future research and development activities are needed. There are various approaches and combinations of approaches which include: ventilation, source control, contaminant control, human factor control, and warning devices.

Other specific control technology research areas include establishing the need and developing the mechanisms for heat recovery from exhaust air; improving the level of control provided by recirculating range hoods and forced air heating systems (e.g., with charcoal filtration); developing end-of-service life indicators for filtration devices; development of a low-cost CO detector; and studying the feasibility of detector-source-control interlock systems.

Other research needs of potential interest to GRI include improved devices for monitoring personal exposure and data collection to support the development of exposure models. Finally, this study itself represents one of the first attempts to develop a health risk assessment process for indoor air pollutants. Now that the foundation has been established, GRI should continue to support the collection, review, and evaluation of information related to indoor air quality and should periodically provide the research community with updates on the status of current knowledge. A continuation of this process will help to guide future research and development efforts and, eventually, will be able to assimilate risk parameters or dose-response data as it becomes available from current and future epidemiological studies.

1. INTRODUCTION

In recent years the national concern for energy conservation has increased dramatically. Many households, spurred by rising energy costs and federal tax incentives, have installed additional home insulation and weather-stripping to reduce the infiltration of cold outside air and the loss of heat by radiation. Concurrently, the role that these measures have on indoor air quality has been called into question.

The public has become concerned about indoor air quality. Recent examples which evoked public concern include bacterial contamination of ventilation systems (Legionnaires Disease), radon in houses built on mine tailings, and hypersensitivity to emissions from urea-formaldehyde insulation. More recently, attention has focused on the chronic health effects of low-level exposure to the products of fossil fuel combustion.

The Gas Research Institute (GRI) has taken an active role in the issue of indoor air quality because of a long-standing interest in energy conservation and their responsibility to protect, to the fullest extent possible, the health of consumers who use gas-fired appliances or are exposed to their emissions. The evolution of the indoor air quality program at GRI is exemplified by the change in focus of this study which initially was conceived under the title of "Air Infiltration" and emphasized effective energy conservation and which now, as the current title suggests, emphasizes the potential health effects which may result from implementing energy conservation measures.

Because of the specific focus of the Gas Research Institute, this study concentrates on gas appliances, particularly gas ranges in kitchens, and their impact of indoor air quality; however, it should be noted that indoor air pollution results from a wide variety of sources and their relative contributions are difficult to assess.

Subsequent chapters in this report address current knowledge regarding the quality of indoor air, the association between indoor air pollution and adverse health effects, the nature of air infiltration, energy conservation trends for reducing air infiltration, and the relationship between indoor and outdoor pollutant sources. Finally, based upon the controversies and gaps in current knowledge identified in these chapters, recommendations are made for further research concerning indoor air quality. A survey of national and international air pollution standards is also included.

2. INDOOR AIR QUALITY

2.1 OVERVIEW

Investigators have used a variety of different instrumentation and analytical techniques to characterize the quality of indoor air. These techniques and instruments range from manual and/or integrated sampling methods to continuous automatic real-time sampling methods. The objectives of this chapter are: 1) to characterize the types of pollutants which have been identified in the residential environment; 2) to review the types of air-sampling instrumentation and sampling methodologies; and 3) to provide a summary of results from selected indoor air pollutant studies which utilize representative measurement techniques.

2.1.1. Identification of Indoor Air Pollutants

The types of indoor air pollutants can be divided into gaseous and particulate pollutants. Table 2-1 describes the various types of indoor pollutants and their sources. Gaseous pollutants include carbon monoxide (CO), nitrogen dioxide (NO_2), nitric oxide (NO), sulfur dioxide (SO_2), carbon dioxide (CO_2), ozone (O_3), ammonia (NH_3), and formaldehyde (HCHO). Additional gaseous pollutants which have been measured in the residential environment are total non-methane hydrocarbons (including fluorocarbons) and a wide variety of organics (various solvents and vinyl chloride). Particulate pollutants include the total suspended particulate (TSP), respirable suspended particulate (RSP), lead (Pb), water soluble sulfates ($SO_4^{=}$) and nitrates (NO_3^-), smoke and radon daughters attached to particulates. Table 2-1 shows that the sources of these pollutants are numerous and include heating systems, cooking appliances, building construction materials, consumer products, and human activities (smoking, etc.). The focus of subsequent discussions will be on the pollutants most widely studied and defined by current indoor pollutant research, particularly those associated with the use of unvented residential heating and cooking appliances.

Carbon monoxide is considered to be a relatively stable reaction product of the incomplete combustion of fossil fuels and is produced when there is insufficient oxygen present due to improper mixing of air and fuel during combustion. The largest source of outdoor levels of carbon monoxide is the automobile, followed by power plants and industrial processes. Mobile fuel combustion sources contribute to approximately 75% of the total established emissions of carbon monoxide in the U.S. [1]. Indoor sources of CO include combustion associated with unvented or faulty heaters and other appliances and cigarette smoke.

In the outdoor environment oxides of nitrogen are produced in high-temperature combustion. Molecular nitrogen and oxygen react to form nitric oxide (NO) at temperatures of 1000°C or above. After mixing with the ambient air, NO is oxidized to nitrogen dioxide (NO_2) which is very reactive with ultraviolet light and subsequently is a major contributor

TABLE 2-1

EXAMPLES OF INDOOR AIR POLLUTION IN RESIDENTIAL BUILDINGS

Sources	Pollutant Types
OUTDOOR	
Ambient Air	SO_2, NO, NO_2, O_3, Hydrocarbons CO Particulates
Motor Vehicles	CO, Pb
INDOOR	
Building Construction Materials:	
Concrete, Stone	Radon
Particleboard	Formaldehyde
Insulation	Formaldehyde, Fiberglass
Fire Retardant	Asbestos
Adhesives	Organics
Paint	Mercury, Organics
Building Contents:	
Fossil Fuel Combustion (gas, oil, coal)	CO, SO_2, NO, NO_2, Particulates
Furnishings	Organics, Odors
Water Service, Natural Gas	Radon
Human Occupants:	
Metabolic Activity	CO_2, NH_3, Organics, Odors
Human Activities:	
Tobacco Smoke	CO, NO_2, HCN, Organics, Odors
Aerosol Spray Devices	Fluorocarbons, Vinyl Chloride
Cleaning and Cooking Products	Hydrocarbons, Odors, NH_3
Hobbies and Crafts	Organics

Source: C.D. Hollowell et al., 1979.

to photochemical smog in populated urban areas. The behavior of oxides of nitrogen in the indoor environment, particularly the conversion of nitric oxide to nitrogen dioxide, is not well understood.

Stern, in a discussion of outdoor sources of the oxides of nitrogen, states the "Nitric oxide is formed to the extent of less than 0.1% to about 0.5% at flame temperatures, along with much smaller amounts of nitrogen dioxide, during combustion of all types of fossil fuels." [2] This percent of NO is highly variable depending on the design features of the combustion apparatus and its method of operation. Indoor sources of NO, NO_2, and NO_x are heating and cooking appliances and NO_2 has also been identified in cigarette smoke. Because of a lack of knowledge regarding the emission of NO in the indoor environment, its rate of conversion to NO_2 and its eventual decay, definitive characterization of exposure to oxides of nitrogen is exceedingly difficult.

Sulfur is a natural constituent of coal and is used in various industrial processes. Sulfur dioxide is a colorless gas with an odor detectable at 0.5 to 0.8 ppm. It is more soluble in water than CO, NO, and NO_2 and reacts with water, sunlight, and several particulate catalysts to form sulfur trioxide, sulfur tetroxide, sulfuric acid, and organic sulfates. Sulfur dioxide is very reactive and will attack and decompose powdered and alkali metals, fabrics, paper and marble. Indoor concentrations of SO_2 are related to the sulfur content of the fuel used for residential cooking and/or heating and the infiltration of ambient pollutants from industrial and municipal power generation.

Particulates are formed by the grinding or atomization of solids and liquids or by dispersion of fine powders from bulk sources into the air. Definitions of particulates are dependent upon their chemical composition, size distribution, and overall concentration. Particulate indoor air pollution may result from indoor or outdoor combustion sources. Inorganic particulates from combustion may include both metallic elements (lead from automobile exhaust, metals from smelting operations) and materials from the burning of tobacco and fossil fuels. Other sources include household organic dust and outdoor airborne dust from crushing and grinding operations of natural ores, sand, and/or limestone. [3]

An important parameter for characterizing the potential health effects of particulates is their size distribution which is generally divided into those that are respirable or non-respirable. Respirable particulate is considered to have an aerodynamic particle size of less than 10 microns (μ) in diameter, while non-respirable is greater than 10 microns. Examples of particulates and their associated aerodynamic particle size include oil smoke (0.05 - 1.0μ), fly ash (1 - 1000μ), and tobacco smoke (0.01 - 0.5μ). [4] Further characterization of the chemical and physical properties of particulates requires specific composition analysis by sophisticated laboratory techniques.

2.1.2. Quantification of Indoor Air Pollutants

Qualitative and quantitative characterizations of indoor pollutants are performed by monitoring the indoor air. The primary goals of an air monitoring program are to characterize the environment according to the concentration and duration of airborne pollutants. Once these two parameters are determined, an exposure index or scenario can be developed for residential exposure to pollutants.

Measurement of the concentration and duration of airborne pollutants in indoor or outdoor environments has been determined according to two different types of air sampling. Characterization of the ambient outdoor environment is usually determined by 24-hour continuous area sampling. Air quality in the occupational and/or industrial environments has been characterized by the use of both personal and area monitoring techniques. For the most part these sampling techniques were developed in response to specific requirements of air quality standards. Due to the unique patterns of exposure to residential indoor air pollution, it is difficult to apply either the 8- or 10-hr. permissible exposure limits of the workplace (personal sampling) or the outdoor ambient air quality standards. Consequently, new sampling strategies are necessary to evaluate properly indoor air quality. Until recently the majority of indoor air sampling was performed using environmental techniques employing area monitoring of the entire residence. However, both Moschandreas[5] and Spengler[6] have integrated personal sampling into their indoor air sampling methodology. Subsequent sections will review representative air sampling techniques and strategies for CO, NO, NO_2, SO_2, and particulates.

2.2 MEASUREMENT AND EVALUATION TECHNIQUES FOR INDOOR AIR POLLUTANTS

2.2.1. Instrumentation and Analytical Techniques

Sampling of indoor air quality can be conducted using several different time scales depending upon the objectives of the investigator. Current investigators use a variety of time scales ranging from short-term (30 minutes - 24 hours) to long-term (1 - 2 weeks) to characterize the indoor environment. Some researchers have concentrated on following the short-term fluctuations of pollutants from indoor and outdoor sources, while other studies have only focused on the accumulated pollutant concentration over days or weeks. The former method of observing short-term pollutant fluctuations requires continuous-flow or real-time instrumentation and analytical methods, while the latter method can use integrated sampling techniques.

Moschandreas et al.[5], from Geomet Technologies, Inc., and Yocum et al.[7], from The Research Corporation of New England (TRC), have developed mobile instrumentation and sampling systems which measure short-term (minutes - hours) or long-term (days - weeks) variations in indoor pollutant levels. Moschandreas et al. described the sampling system they used in their 1978 and 1980 studies:

> A mobile laboratory fully equipped with the necessary monitoring equipment was placed in close proximity to the structure being monitored. Pollutant concentrations were measured at one location outdoors (adjacent to building) and three locations indoors (typically the kitchen, bedroom, and living room). Four minute samples of gaseous pollutants are obtained three times each hour from a continuous monitoring system which is used in conjunction with a programmable solenoid switching mechanism at each of the four sampling locations.[10]

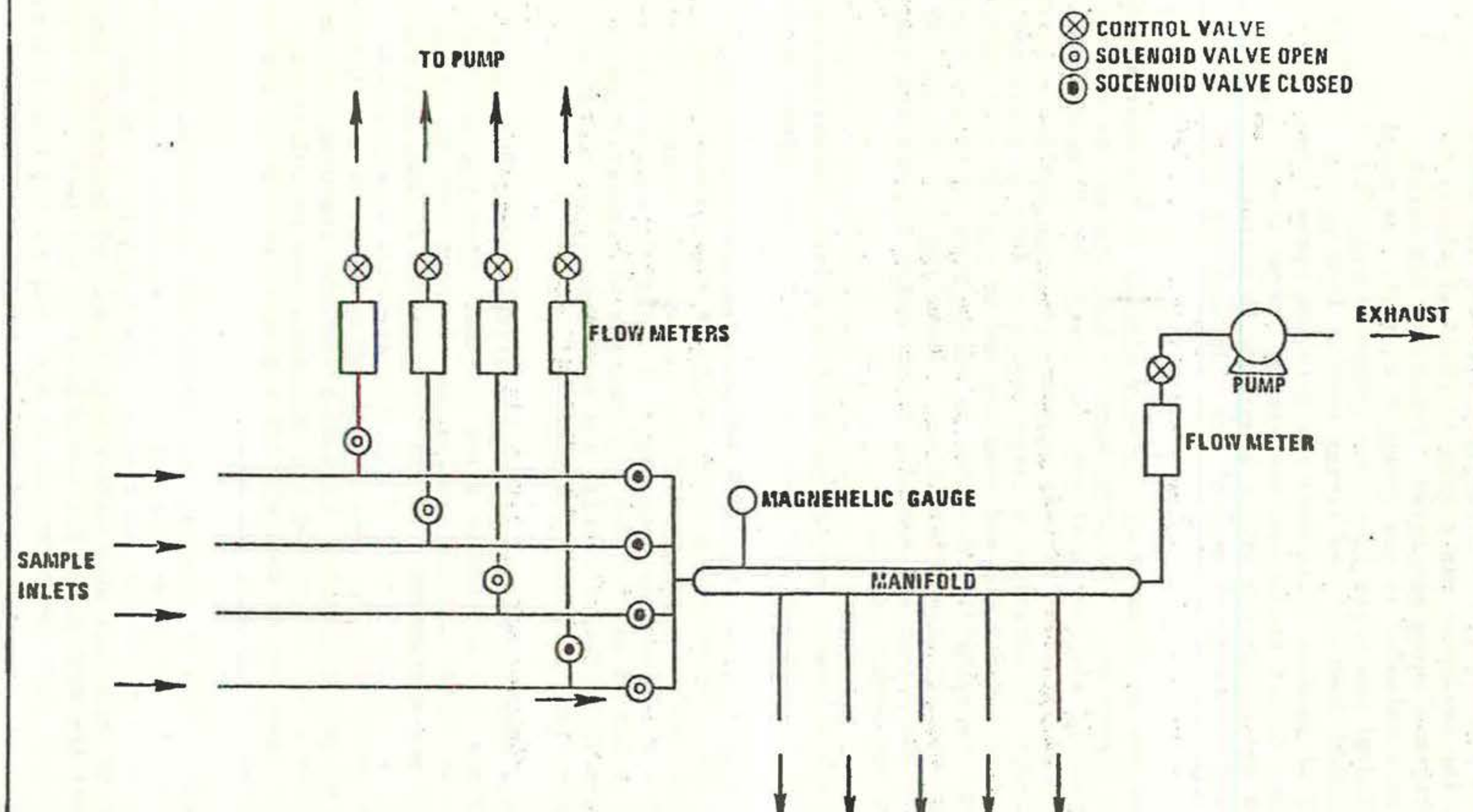
The system developed by Yocum et al. is very similar to the Moschandreas system shown in Figure 2-1. The advantages of this system, as opposed to traditional sampling, are less equipment for transport and maintenance and less analytical variation between instruments (when duplicate instrumentation is used). In addition, a large amount of data is collected to characterize indoor air quality and sampling can be applied over different time frames. Consequently, data can be manipulated to follow hourly, daily, and weekly pollutant concentrations. (Sampling for TSP and RSP was performed by the integrated sampling method using filters and pumps in both the TRC and Geomet studies.)

In addition to the automatic continuous sampling system, investigators have applied manual integrated sampling and instantaneous (grab) sampling. Spengler et al.[6], in their six-city prospective epidemiological study used the West-Bache (SO_2) and modified sodium arsenite-bubbler (NO_2) integrated methods. The sampling train consisted of a vacuum pump, connective tubing, and an impinger with the appropriate reagent. This method allows for a twenty-four hour sample followed by analysis in the laboratory. This method only allows for analysis of cumulative daily or weekly changes in pollutant levels, and consequently is not at all sensitive to short-term pollutant fluctuations.

The instantaneous sampling method allows for a cross-sectional analysis of pollutant levels at a particular point in time. Sterling and Sterling[9] used this method in their evaluation of short-term CO levels in kitchens with gas appliances. In the first phase, CO sampling was performed using an Ecolyzer* every 2 - 5 minutes for a ninety-minute period. In the second portion, samples were taken at 0, 30 and 90 minutes after use of gas appliances. Depending upon the frequency of sampling, this approach may not adequately represent peak pollutant concentrations over time, but it does provide a general picture of concentrations and trends of emission and decay.

There are numerous types of sampling instruments and analytical techniques. Examples of continuous constant flow and automatic methods are listed in Table 2-2 for several pollutants. The validity of an analytical technique is dependent upon sensitivity (limit of detection) and specificity. For the most part, the specificity of the techniques listed in Table 2-2 is good with the exception of SO_2. Due to its high reacti-

*Ecolyzer is a trademark of Energetic Science, Inc.



SOURCE: D. J. Moschandreas et al., 1978.

FIGURE 2-1 SAMPLING SYSTEM FOR CONTINUOUS MONITORS

TABLE 2-2

EXAMPLES OF CONTINUOUS MONITORING EQUIPMENT
AND THEIR SPECIFICATIONS FOR MONITORING INDOOR-OUTDOOR POLLUTANTS

Pollutant	Principle of Detection	Manufacturer, Model	Concentration (ppm) Range(s)	Concentration (ppm) Limit of Detection	Response Time to 90% or Greater (Sec)	Precision
NO	Chemiluminescent	Meloy NA-520-2	0-0.5 0-1.0 0-2.0 0-5.0	0.005	100 s	± 1% Full Scale
NO_x ($NO + NO_2$)	Chemiluminescent	Meloy NA-520-2	0-0.5 0-1.0 0-2.0 0-5.0	0.005	100 s	± 1% Full Scale
CO_2	Nondispersive Infrared	Beckman-865	0-2,500 0-50,000	25 500	2.5 s	± 1% Full Scale
CO	Nondispersive Infrared with flowing Ref. Cell	Beckman-865	0-50	0.50	2.5 s	± 1% Full Scale
O_3	Chemiluminescent	Melov-OA-350-2	0-0.5	0.005	15 s	± 2% Full Scale
SO_2	Flame Photometric	Meloy-SA-185-2A	0-0.5	0.005	60 s	± 1% Full Scale
CH_4	Flame Ionization with Selective THC Oxidizer	MSA-11-2	0-5 0-20	0.05 0.20	15 s	± 1% Full Scale
THC	Flame Ionization with Selective THC Oxidizer	MSA-11-2	0-5 0-20	0.05 0.20	15 s	± 1% Full Scale

SOURCE: D.J. Moschandreas et al., 1978

vity, SO_2 has always been difficult to measure in the air. Yocum et al.[7] used a conductimetric analyzer for SO_2 analysis. The analyzer was affected by CO_2 interference at low levels of SO_2 due to a poor H_2S scrubbing system. Moschandreas[9] in his 1978 study found that during the period of summer sampling for SO_2 at various homes, high levels of CO_2 "squelched" SO_2 levels when measured by flame photometry. Again the problem was traced to a deficient H_2S scrubber. Further testing by Moschandreas found that " . . . interference of SO_2 concentrations does occur with variation of CO_2 concentrations. This interference takes place over the range of CO_2 concentrations normally found during the indoor-outdoor air sampling program."[10] For the most part, the relationship between SO_2 and CO_2 was linear; consequently, a correction factor was applied to account for the CO_2 interference.

In addition to the continuous automatic sampling and analytical methods, there are numerous other integrated manual and instantaneous methods for measurement of CO, NO, NO_2, SO_2, TSP, and RSP. Both Derham et al.[19] and Sterling [9] utilized the CO Ecolyzer, a direct-reading instrument, for their instantaneous sampling. The Ecolyzer has very good reproducibility down to concentrations of 0.5 ppm of CO [9].

Due to the expense and level of effort required for measurement of NO, NO_2, and NO_x with continuous chemiluminescence, many studies used manual integrated instrumentation based on colorimetry. The continuous Griess-Saltzman colorimetric technique with modifications is widely used to measure NO_2. Recently, the Environmental Protection Agency (EPA) discredited the Jacobs-Hochheiser manual technique as a method for determination of ambient NO_2 levels because of considerable interference from NO and lack of precision. [21]

A new integrated sampling method for measurement of NO_2 developed by Palmes et al.[11] has been utilized by Melia et al.[17]to measure indoor pollution. The principle of the sampler is based on the transfer of NO_2 by diffusion to a triethanolamine-coated collector followed by analysis with spectrophotometry. The sampler can be placed in an indoor environment and left in place for days to weeks. Goldstein et al.[12] reported that the diffusion tube samples compare favorably with the highly specific chemiluminescent NO_2 technique. The simplicity of the instrumentation and length of the sampling period (during which no technical input is necessary) are advantageous for general characterizations of indoor NO_2 levels. However, a major disadvantage of the NO_2 diffusion tube is the inability to determine short-term fluctuations.

The application of these methods for the assessment of indoor air quality has been restricted for the most part to area sampling. Personal sampling for the measurement of CO, NO, NO_2, SO_2, and particulates is common in occupational applications and has recently been adopted for indoor air quality. The passive diffusion NO_2 monitor is intended for use as a personal sampler, but to date it has been more commonly utilized for area sampling. The integrated manual personal sampling techniques for NO_2 apparently are being utilized in the Six-City Study.

Geomet, Inc., has developed a new type of personal sampler to characterize indoor air quality. A description of the new instrumentation states that:

> . . . The Geomet Personal Sampler provides a method for sampling air in proportion with the respiration of the wearer. The method is characterized by its use of a carefully designed air pump which is supported next to the diaphragm. The pump is activated by the expansion and contraction of the thoracic cavity during respiration and draws air through a collector which may be varied in accordance with monitoring requirements.[5]

The air sample is drawn (by the diaphragm pump) through a tube coated with an absorbent and then analyzed in the laboratory using the appropriate technique. To date only a limited amount of NO_2 sampling has been reported.

Finally, the most important component of any monitoring program under field conditions is a quality control program. For example, the rate of airflow must be periodically monitored to ensure the proper volume of air for a mass per volume calculation. Likewise, the specificity and sensitivity of the analytical technique for the monitored atmosphere must be checked. Both of these issues are important in evaluating the quality of any air sampling program. A comprehensive quality control program was developed by Moschandreas et al [10] and is described in Volume II of their report.

2.2.2. Representativeness and Relevance of Air Sampling Measurement

An important objective of an air sampling program is to develop a representative and relevant profile of population exposures. Factors which are important for exposure assessment include: the length and number of the sampling periods; the location of sampling points; and the selection of persons to sample. Some of the factors which can influence the representativeness of non-personal exposure data include:

- Proximity of the monitoring site to the pollutant source relative to that of the exposed population (power plants, automobiles, appliances, furnaces).
- Weather parameters, wind speed and direction (for outdoor sources affecting indoor levels based on infiltration, etc.).
- Reactivity of a pollutant.
- Pollutant emission by a few large point sources vs. many small sources scattered throughout the area.

One of the most influential factors with respect to indoor exposure (which to some extent may reflect outdoor pollutant levels) is the location of monitoring sites in relation to the pollutant sources, and the frequency and duration of pollutant emission from these sources. Investigators have implemented a variety of sampling strategies to assure that exposure data are representative. Yocum et al.[15] characterized indoor air quality with sampling points at locations far outside, near outside, near inside, and far inside the test houses. Potential indoor and outdoor pollutant sources were characterized and inside to outside ratios were calculated.

Moschandreas et al.[8] felt that a one-zone (indoor) approach adequately reflected pollutant levels (backed up by sampling at three indoor sites, which were statistically averaged). They attempted to answer the following questions: "Do indoor zones (independent areas) with distinct pollutant patterns exist? Does the hourly average of the three corresponding indoor concentrations adequately characterize the residential air quality?" In addition to the three indoor samples (kitchen, dining room, bedroom), an outdoor sample in close proximity to the residence was also taken.

The six-city study has employed a unique sampling strategy to characterize indoor and outdoor air quality and to develop an exposure index for each participant. The strategy is a three-stage, aerometric monitoring system which includes: continuous ambient monitoring at a central site; an array of indoor and outdoor satellite monitors; and, finally, on a limited basis, personal monitoring.

2.3 SUMMARY OF INDOOR AIR SAMPLING STUDIES

The two previous sections have identified the common indoor air pollutants, their measurement techniques, and the problems related to representative sampling. This section will discuss the results of recent studies which are summarized in Table 2-3. In these discussions, comparisons between findings and standards are intended as reference points. Because of variation in sampling instrumentation and analytical technique, location of monitoring, and duration of sampling periods, direct comparisons to standards and between investigators are difficult.

2.3.1 Nitrogen Dioxide

In their most recent study, Moschandreas et al. [5] found a maximum one-hour NO_2 concentration of 0.28 ppm indoors according to their one-zone sampling concept in several homes. As can be seen in Table 2-3, Hollowell demonstrated in the laboratory that short-term NO_2 levels (two hours) ranged from 0.1 - 0.75 ppm as a function of decreasing air exchange rates. Palmes[16] and Melia[17] in their indoor NO_2 evaluations used the passive diffusion sampler and cited hourly averages. The integrated sampling technique measures accumulated NO_2 concentrations over an extended period (96 hours for Melia) and then the number of sampling hours is divided into the overall concentration for an hourly average. Using this method, Melia reported hourly averages of 0.072 ppm and 0.0095 ppm for gas and

TABLE 2–3

INDOOR AIR POLLUTANT MEASUREMENTS

AUTHOR/YEAR	NO ppm	NO_2 ppm	NO_x ppm	CO ppm	CO_2 ppm	SO_2 ppm	TSP $\mu g/m^3$	RSP $\mu g/m^3$	SMOKE $\mu g/m^3$	REMARKS
Belles, et al; 1976[1]			(172.7)							– Gas range burner/blue flame/18 ranges sampled once.
			(244.7)							– Room heater/blue flame/no. samples unknown.
			(215.9)							– Water heater/blue flame/ 17 heaters sampled once.
										(All samples taken in flue ductwork.)
Biersteker, 1965						0.015 s = 0.018			163 s = 63	(60 homes sampled/24-hr average/mean of 1 wk/1 area sample in living room (SO_2 by titration))
Cote, et al; 1974	0.083–0.11	0.036–0.063		3.07–3.9						– 1 home/24-hr average/kitchen/F,W,S[6]/ 4–9 days of sampling/oven and burner on an average of 169 min/day.
Derham, et al; 1974[2]	0.08–0.3	0.01–12		0.0–0.0026						(24-hr average. 3 a.m.–3 p.m./measurements at ventilation ductwork/concentration ranges for typical daily patterns'/1-office bldg. no indoor sources.)
Goldstein, et al; 1979		0.112								– Wk average/gas kitchen area sample/ S.E. = 0.0027 ppm. range 0.005–0.32 ppm.
		0.018								– Wk average/electric kitchen area sample/ S.E. = .0024 ppm, range 0.008–0.118 ppm.
										(Palmes NO_2 passive dosimeter used.)
Hollowell, et al; 1975[2]	0.003	0.001		4.5		0.0006				– Kitchen/mean value/pilot light only.
	0.40	0.08		7.7		0.0009				– Kitchen/mean value/cooking only.
	2.1	0.58		34.5		0.001				– Kitchen/max value/cooking only (5 homes with gas stoves, 24-hr average sampling, no. of sample dys unknown.)
Hollowell, et al; 1978[2]		0.75–1.5		18–48						– 0.24 ACPH/2-hr sample/gas oven on 1 hr.
		0.25–0.75		9–22						– 1.0 ACPH/2-hr sample/gas oven on 1 hr.
		0.1		3						7.0 ACPH/2-hr sample/gas oven on 1 hr. (Laboratory chamber was 27 m^3.)
Hollowell, et al; 1979		1.2								– 0.24 ACPH/no stove vent.
		0.40								– 2.5 ACPH/stove hood fan at 50 cfm.
		0.10								– 7.0 ACPH/stove hood fan at 140 cfm. (Gas oven on 1 hr at 350°F in experimental test kitchen.)
Lefoe, et al; 1971[2]								678(3) s = 307(3)		– 0.3 μ particle size/without filter/ 10 a.m.–4 p.m.
								246(3) s = 167(3)		– 0.5 μ particle size/without filter/ 10 a.m.–4 p.m.
								147(3) s = 106		– 1.0 μ particle size/without filter/ 10 a.m.–4 p.m. (Measurements in flue ductwork, means of 3 residences, 1 measurement each hr of 1-minute duration.)
Lefoe, et al; 1975[2]								767(3)		– 0.3 μ particle size/7 a.m.–12 p.m.
								2033(3)		– 0.5 μ particle size/7 a.m.–12 p.m.
								417(3)		– 1.0 μ particle size/7 a.m.–12 p.m. (Measurements in flue ductwork, means of 3 residences/measurement each hr of 1-minute duration.)
Macriss, et al; 1977		0.066								– 24-hr average. light cooking/3 homes.
		0.082								– 24-hr average/average cooking/ 5 homes.
		0.099								– 24-hr average/heavy cooking/5 homes.

1. ( ) = Emission levels, units are in micrograms per Kcal of Heat.
2. Approximations of graphs or charts in text.
3. Particle counts (1000's/cubic foot).
4. Figures are from text.
5. Sampling technique was based on sedimentation foils which were 27 centimeters square. Units are in milligrams per foil (mg/foil).
6. S = Summer
   F = Fall
   W = Winter

s = Standard deviation
S.E. = Standard error
Max = Maximum value
ACPH = Air changes per hour

TABLE 2–3
(Continued)

AUTHOR/YEAR	NO ppm	NO_2 ppm	NO_x ppm	CO ppm	CO_2 ppm	SO_2 ppm	TSP $\mu g/m^3$	RSP $\mu g/m^3$	SMOKE $\mu g/m^3$	REMARKS
Melia, et al; 1978		0.072								– Gas kitchen/2 kitchens/hourly average.
		0.0086								– Electric kitchen/2 kitchens/ hourly average. (Gas stove on 8.5–10 hrs over 96-hr sampling period, kitchen area sampled no exhaust hoods. Palmes NO_2 dosimeter.
Moschandreas, et al; 1980	0–0.3/ 470 max[2]	0.180[2] max		2.0-range 0–3.6[2]		30-100[4] max=900				– 24-hr average/typical home with range and/or max value.
							46–62			– 24-hr average/mean range for 6 homes with smokers.
							8–35			– 24-hr average/mean range for 8 homes without smokers. (Zone concept-indoor samples averaged)
Moschandreas, et al; 1980				10						– Max 8 hrs
		0.28		13						– Max 1 hr
							480			– Max 24 hrs (Zone concept-indoor samples averaged.)
Palmes, et al; 1979		0.003								– No unvented appliances/4-home average.
		0.130								– Unvented space heater/3-home average.
		0.222								– Unvented space heater in 2 rooms/ 2-home average. (Hourly average exposure – Palmes NO_2 passive dosimeter.)
Schaefer, et al; 1972[2]						1.25[(5)]				– 867 homes in Chicago, Washington, Austin & Atlanta with windows closed.
						1.8[(5)]				– 38 gas kitchens.
						1.4[(5)]				– 18 electric kitchens. (Average of 30-day period.)
Spengler, et al; 1979[2]					0.003-range 0.0008–0.008		34.0-range 20–48			– Annual arithmetic mean/6 cities/one indoor sampling site.
		0.012-range 0.004–0.024								– Annual arithmetic mean/6 cities/electric kitchen.
		0.022-range 0.01–0.028								– Annual arithmetic mean/6 cities/gas kitchen.
Sterling, et al; 1979[2]				28.9-range 20.5–38 61.8 (kitchen, 9 homes, after 20 min. of cooking)						– Average of living & dining room levels/ 4 homes/0 min. after gas stove on 21 min./ grab sample.
				17.0-range 8.75–29						– Average living & dining room/ 4 homes/ grab sample 90 min. after stove on for 20 min.
Thompson, et al; 1973						84				– One home/24 hrs/no primary filtration.
						11				– One home/24 hrs/with secondary filter-electrostatic precipitator.
Yocum, et al; 1970				5.69		0.030	103			– 24-hr average/1 home/three two-week sampling periods/S.F.
				5.11		0.033-range .007–.066				– 24-hr average/1 home/three two-week sampling periods/S.F.
								21.0		– 12-hr average/1 home/3-day sample/ W.F/<25μ particles.
								34.3		– 12-hr average/1 home/3-day sample/ W.F/<25μ particles. (All one indoor sample location)
	(91.4)[1]	(73.1)[1]		(530)[1]						– Older gas stove/steady state.
	(77.9)[4]	(20.4)[1]		(1.820)[1]						– Newer gas stove/steady state.

1. ( ) = Emission levels, units are in micrograms per Kcal of heat.
2. Approximations of graphs or charts in text.
3. Particle counts (1000's/cubic foot).
4. Figures are from text.
5. Sampling technique was based on sedimentation foils which were 27 centimeters square. Units are in milligrams per foil (mg/foil).

6. S = Summer
   F = Fall
   W = Winter

s = ~~Standard deviation~~
S.E. = Standard error
Max = Maximum value
ACPH = Air changes per hour

electric kitchens, respectively. Similarly, Palmes reported hourly NO_2 levels as a function of vented or unvented gas appliances. He found an NO_2 hourly average of 0.222 ppm in homes with two unvented space heaters. Presently, there is no Federal ambient air quality standard for hourly NO_2 levels; however, California and Colorado do have hourly NO_2 standards of 0.25 ppm and 0.10 ppm. Both Hollowell's experimental NO_2 levels and Palmes' unvented space heaters are approaching these standards, but they are well below OSHA's PEL for NO_2 of 5 ppm as an eight-hour time-weighted average as well as the proposed ceiling standard of 1 ppm averaged over 15 minutes. It should be noted that even under seemingly worst-case conditions (i.e., a small volume experimental chamber or unvented space heater use), NO_2 levels may not be excessive.

The ambient air quality standard for NO_2 is an annual arithmetic mean of 0.05 ppm. The initial reports of the six-city study offer direct comparisons with ambient air quality standards. Indoor air sampling (one site) resulted in an annual arithmetic mean of 0.012 ppm (0.004 - 0.024 ppm) for electric kitchens and a mean of 0.022 ppm (0.01 - 0.028 ppm) for gas kitchens. The level for gas kitchens is approximately one-half the ambient air quality standard. The accuracy of these results is uncertain because the sodium arsenite bubbler technique is subject to interference particularly from carbon dioxide. Other investigators have measured NO_2 over 24 hours including 0.098 ppm during heavy cooking on a gas range (Macriss, 1977), 0.180 ppm maximum in a typical home with a gas range (Moschandreas, 1978), and 0.036 - 0.053 ppm in a kitchen one meter from the stove with the gas oven and burner operating for about three hours per day (Cote et al., 1974). Goldstein found an average NO_2 level of 0.112 (0.005 - 0.32 ppm) over a one-week period in a kitchen with a gas stove. Initially this study involved a sample of 516 homes, but comprehensive sampling and follow-up inspections were restricted to 58 homes. In a recent presentation [13] Goldstein remarked that, in some cases, the cooking stoves were located in a room which was separated from the regular kitchen/living area. This fact further complicates any correlation between measured levels and individual exposures.

2.3.2 Carbon Monoxide

Both Hollowell[14] and Sterling [9] have concentrated their investigations of indoor air quality on peak CO levels in close proximity to gas appliances. As can be seen in Table 2-3, Sterling found CO peaks of approximately 62 ppm (nine homes) after the gas range had been on for 20 minutes. In four of these homes, peak CO levels in the living and dining rooms of 29 ppm (range of 20.5 - 36) dropped off to 17 ppm (8.75 - 29) 90 minutes after stove use. In the laboratory, Hollowell found a range of CO levels of 16 - 49 ppm over two hours (gas stove on for one hour) at 0.24 air changes per hour (acph) in an experimental chamber. At one acph, these CO levels dropped down to 9 - 22 ppm. Hollowell and Sterling also reported that peak levels varied when cooking utensils were used on the stove. Some of these short-term levels are significant when compared with the one-hour ambient air quality standard for CO of 35 ppm, but are well below the 15-minute American Conference of Governmental Industrial Hygienists (ACGIH) Threshold Limit Value--Short-term Exposure Limit (TLV-STEL) of 400 ppm. A fundamental problem with laboratory studies or short-term studies of small samples of houses is that inferences regarding human exposure can not be well supported.

A number of investigators have also measured indoor CO over a 24-hour period using continuous automatic sampling methods. In the field, Hollowell [14] found mean kitchen CO levels of 7.7 ppm during gas cooking only and a mean CO level of 4.5 ppm in the kitchen with only the gas pilot light in operation. Moschandreas[5], employing the one-zone concept throughout a residence, found maximum CO levels of 10 ppm over eight hours and 13 ppm during one hour. Finally, Yocum[7,15] found mean 24-hour CO levels over three two-week sampling periods (at one indoor sampling site) of 5 - 6 ppm. In addition, similar sampling periods revealed CO levels of 3 - 4 ppm in one home when the oven and burner were in operation approximately three hours throughout the day. For the most part these levels are in the range of the eight-hour ambient standard of 9 ppm and well below the Occupational Safety and Health Administration's (OSHA) Permissible Exposure Limit (PEL) of 50 ppm for an eight-hour time-weighted average (TWA). The time-frame of these studies provides a more representative understanding of CO levels in the indoor environment but, again, the data is restricted to a small number of samples. Also, it is difficult to quantify the contribution of diffuse sources of CO such as smoking and automobile exhaust.

2.3.3 Sulfur Dioxide

Because of reactivity, investigators have had limited success in measurement of indoor SO_2 levels. Biersteker[20] in his 1965 study found a 24-hour SO_2 average of 0.015 ppm in 60 homes sampled in the living rooms (the analytical technique used was titration to total acidity). Again, as seen in Table 2-4, Spengler[6] reported an indoor annual arithmetic mean of 0.003 ppm (0.0008 - 0.008 ppm). This falls well below the ambient air quality standard annual arithmetic mean of 0.03 ppm for SO_2. On the other hand, Yocum [7] reported a 24-hour average in one home of 0.033 ppm (0.007 - 0.066 ppm). The 24-hour ambient air quality standard for SO_2 is 0.14 ppm. All of these reported levels are well below the OSHA PEL of 2 ppm and the 15-minute, short-term TLV-STEL of 5 ppm.

2.3.4 Suspended Particulates

Only two investigators have specifically measured total suspended particultes (TSP) levels. These range from 30-100 $\mu g/m^3$ (Moschandreas, 1978) to 103 - 108 $\mu g/m^3$ (Yocum, 1970).

In terms of health effects, the most important portion of TSP is the respirable suspended particulates (RSP) for which there are no federal ambient air quality standards. Spengler [6] reported an indoor annual arithmetic mean for RSP of 30 $\mu g/m^3$ (20 - 48 $\mu g/m^3$). Twenty-four hour indoor RSP for six homes with smokers were 46 - 85 $\mu g/m^3$, while eight homes without smokers had RSP levels of 8 - 35 $\mu g/m^3$ [8]. Reference standards are the OSHA standard of 5,000 $\mu g/m^3$ for respirable inert or nuisance dust as an eight-hour TWA and the maximal 24-hour average ambient air quality standard for TSP of 260 $\mu g/m^3$. Preliminary personal sampling results on 46 subjects in Topeka, Kansas describe the variation of mean RSP levels over a seven-week period with a peak of 40 $\mu g/m^3$ and a range of values down to 20 $\mu g/m^3$.

Again, the problem of relating measured levels to personal exposure must be mentioned. An additional problem for particulates is that the toxic effects will vary depending upon the size and chemical nature of the particles.

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3. HEALTH EFFECTS OF INDOOR AIR POLLUTION

3.1 INTRODUCTION

This chapter contains an assessment of the scientific evidence which purports to show a relationship between exposure to pollutants in the residential environment and adverse health effects. This assessment focuses on nitrogen oxides as pollutants generated by indoor combustion processes or by infiltration from outdoors and briefly addresses other combustion-generated pollutants such as carbon monoxide.

After reviewing the scientific literature, many questions regarding the health effects of exposure to low levels of nitrogen dioxide remain unanswered. In part, this results from incomplete and conflicting epidemiological data. To assess the association between nitrogen dioxide exposure and health effects, data on all sources of exposure are required including indoor as well as outdoor sources. In addition, the types and levels of other pollutants to which the public may be exposed must be fully characterized. Most existing epidemiological studies, however, are restricted to a single source such as the residential or occupational environment and, therefore, the results of such studies are questionable.

Unfortunately, even the limited amount of exposure data which is collected in studies of indoor pollutant health effects suffers from fundamental problems. For example, gas cooking has been used as a surrogate measure which implies elevated indoor levels of oxides of nitrogen and, thus, implies elevated exposure. Such a surrogate measure ignores variables such as the frequency and duration of appliance use, venting of appliances, sources and amounts of infiltration, and occupant activities which may have a considerable influence on exposures. Other problems with indoor pollutant epidemiology studies include the quality of pollutant measurements and the effect of confounding variables such as smoking or socioeconomic status on health.

While epidemiological studies provide the most representative approach for describing the relationship between pollutant exposure and human health effects, they are complex and subject to numerous sources of bias. On the other hand, experimental human and animal exposure studies in the laboratory can be more easily controlled but they are less representative of actual exposures. Furthermore, clinical or experimental studies measure response variables such as subtle changes in pulmonary function which may signify a healthy adaptive response to an irritant rather than a pathological response or adverse health effect. Experimental animal studies are difficult to interpret because there are no satisfactory models for extrapolating health effects from animals to man.

In summary, serious problems associated with epidemiological studies of exposure to indoor air pollutants have been identified. Overall, the data are limited, imprecise, and contradictory. Clinical data are not representative of actual exposures and results from animal toxicological studies are difficult to extrapolate to humans. Subsequent sections of this chapter will discuss the health effects of specific pollutants and will assess the validity of several epidemiological studies of populations exposed to indoor air pollutants.

3.2 HEALTH EFFECTS OF AIR POLLUTION

Exposure to air pollutants has been associated with a variety of health effects or responses including excess mortality, acute and chronic respiratory disease, exacerbation of asthma, decrements of pulmonary function, heart disease, and lung cancer. The following sections will address the health effects of the major pollutants found in the residential environment. The focus of this review is pollutants associated with gas combustion particularly carbon monoxide and nitrogen dioxide. Sulfur dioxide, particulates, and other contaminants are addressed briefly. Comprehensive reviews of the health effects of air pollutants are available. [1,2,10]

3.2.1 Oxides of Nitrogen

The association between nitrogen dioxide (NO_2) exposure and health effects is a controversial subject because NO_2 is frequently associated with other pollutants such as ozone, sulfates, and particulates, and it is difficult to assess their relative effects. Furthermore, much of the monitoring data in NO_2 epidemiological studies is frequently of poor quality because it was collected using inaccurate sampling and analytical methods. Finally, at low levels of exposure the observed effects such as increased airway resistance may indicate normal adaptive responses rather than early signs and symptoms of disease.

3.2.2 Carbon Monoxide

The toxic effects of carbon monoxide result from the production of carboxyhemoglobin which restricts the oxygen-carrying capacity of the blood and results in a tissue deficit of oxygen such that normal functions are compromised. Persons with chronic diseases such as arteriosclerosis or symptoms such as angina pectoris are less able than the normal person to compensate for an oxygen deficit with increased blood flow and thus are more susceptible to the effects of carbon monoxide exposure. Other health effects associated with carbon monoxide exposure are aberrations of central nervous system function, severity of acute myocardial infarction and arteriosclerosis and vascular disease. On the other hand, carbon monoxide is a normal metabolic product and, in the absence of exogenous CO exposure, COHb concentrations are about 0.5%. Cigarette smokers (1 pack/day) may have COHb levels as high as 4-12%, while nonsmokers exposed to 9 ppm to CO for 8 hours [5,11] or 35 ppm for 1 hour (EPA standards) have COHb levels of 1.5%.

3.2.3 Sulfur Oxides and Particulates

Sulfur oxides and particulates are considered as a complex of pollutants which include gases, aerosols, and particulates and which are commonly products of fossil fuel combustion. Controversy exists whether the health effects observed in SO_2 studies were due to SO_2 or other pollutants. Some investigators have reported that the short-term health effects associated with exposure to this pollutant complex may be increased respiratory symptoms in patients with chronic bronchitis and asthma and changes in pulmonary function. Some studies of long-term health effects have reported an increased incidence of respiratory illness. Findings by some investigators that sulfur dioxide is relatively non-toxic in laboratory animals have led to the conclusion that the active agents may be sulfates and other products of sulfur dioxide transformation in the atmosphere.

3.2.4 Other Pollutants

A variety of other pollutants have been associated with the use of cooking stoves; however, there is little information on levels of exposure or health effects. Speculations have been made regarding the possibility of radon and formaldehyde emissions during gas combustion but they are not generally considered to be a problem. Although their potential carcinogenic properties are a concern, the levels of radon and formaldehyde are not expected to be significant when compared to other ambient and residential sources. The potential emission of compounds such as benzo (a) pyrene and nitrosamines from partially combusted fatty foods has not been investigated and, since exposure may be widespread, efforts should be undertaken to assess the levels of these compounds in the residential environment.

3.3 RECENT EPIDEMIOLOGICAL STUDIES OF THE HEALTH EFFECTS OF INDOOR AIR POLLUTION

Although there has been a massive amount of research on the health effects of air pollution, there are few studies of the health effects of indoor air pollution and no studies which adequately consider the complete exposure profile. Major studies of indoor air pollution include the EPA-Long Island study [15]; several studies in Great Britain by Melia et al. [16-19]; the American Gas Association Indoor Epidemiology Study [22-24] and the on-going Harvard Six-Cities Study [25,26]. The following sections provide brief descriptive comments for each of these studies which are reviewed in greater detail in the annotated bibliography.

3.3.1 Environmental Protection Agency-Long Island Study [15]

This study was part of the EPA Community Health and Environmental Surveillance System (CHESS) and involved middle-class suburban families on Long Island who were queried at two-week intervals about common respiratory ailments. Eighty-seven of the families used gas for cooking, while the remaining 59 families did not use gas. The authors claimed that three out of four family segments (i.e., father, mother, and school-age but not preschool age children) using gas reported significantly higher rates of acute respiratory illness than those not using gas. Although the authors reported a significant difference in illness rates, no calculations are provided and, if the data provided are used to construct contingency tables of gas and no gas cooking and person-weeks reporting illness and not reporting illness, the results do not approach significance (see Appendix I1). Despite the claims of significance, the authors do explain that the study is based upon preliminary data and state that the exposures might be associated with excess disease. Apparently, the study was not completed and the data have not been validated.

3.3.2 Studies in Great Britain [16-19]

Melia et al. [16] presented preliminary results of their study which found various relationships between gas cooking and respiratory disease prevalence in school children. The level of effect appeared to be stronger for girls than for boys and varied from location to location. Adjustment for potential confounding factors tended to reduce the significance of associations although the trend was unchanged. This preliminary study, which was conducted in 1973, was continued until 1977 so that the original population of children could be followed over time and new groups of children could be added to the study population.

Melia et al. [17], Goldstein et al. [18], and Florey et al. [19] have reported the results of the follow-up studies. As in the preliminary study, adjustment for confounding factors led to inconsistent associations. For example, in 1973, the gas cooking effect approached significance only for girls while in 1977, it was only significant for boys.

Moreover, in 1977, a significant association with gas water heaters was observed only for girls. Other anomalies include a shift from a maximum effect in northern urban areas in 1973, to an independence from latitude in 1977. These and other inconsistencies suggested that some third factor sporadically associated with gas cooking might be responsible for the observed health effects. Two logical candidates are variations in humidity and temperature.

Although the casual reader might impute causality from these associations, the authors are more cautious and, in the last paper of the series, they warn that the results "do not provide a definitive answer to the question of whether NO_2 is harmful to health at concentrations in the home" [19]. In this case, the levels measured in 428 kitchens ranged from 0.005-0.317 ppm, with a mean of 0.112 ppm. An interesting finding by Goldstein et al. [18] was that gas cooking homes with higher levels of NO_2 had greater numbers of meals eaten and greater use of the cooker for heating and drying clothes than the lower-level gas-cooking homes. This suggests an association between higher levels of NO_2 and socio-economic factors such as crowding and poverty which may also be associated with respiratory infection and chronic respiratory disease.

Recently, Goldstein [20] reviewed the health aspects of nitrogen oxides and remarked that the data were not clear-cut and that there continued to be a "lingering-doubt" concerning any adverse effects of exposure to the levels of oxides of nitrogen commonly found in the residential environment. In any case, he asserted that the health effects of indoor NO_2 from sources such as the gas range were much less significant than the health effects associated with smoking. Melia [21] in comments presented to the EPA Clean Air Scientific Advisory Committee stressed that their findings on the relationship between indoor levels of NO_2 and the health of children were inconsistent, that the validity of any apparent associations had been exaggerated and that misinterpretation had resulted from a failure to consider the impact of other contributory factors.

3.3.3 American Gas Association Indoor Epidemiology Study [22-24]

This study in a middle class suburb of Columbus, Ohio, examined the incidence of reported respiratory illness and measured lung function in members of 441 households cooking with gas or electricity. In addition, measurements of oxides of nitrogen were taken in 83 gas cooking homes and 50 electric cooking homes. No evidence of an association between reported illness or lung function change and cooking fuel was found. An additional study to verify the data collection methodology consisted of periodic telephone contacts to obtain data on the recent incidence of respiratory symptoms in a subsample of 60 gas cooking homes and 60 electric cooking homes. There are several methodological issues which reduce the strength of the results including the use of an apparent volunteer sample, the potential for interviewer bias, and the lack of personal exposure data. On the positive side, the study population included family members of all ages and thus may be more representative of the total population than studies which focus on children or other sensitive groups such as asthmatics.

The follow-up study was intended to validate the telephone reporting of respiratory illness by conducting physical examinations and to provide a replication of the earlier study. The authors reported sensitivity of 72% and specificity of 91%; however, the calculations may not be appropriate because the population reporting illness was heavily over-sampled relative to the population not reporting illness.

3.3.4 Harvard Six Cities Study [25,26]

The Harvard Six Cities Study is a long-range prospective study on the health effects of exposure to ambient levels of pollutants which result from the combustion of fossil fuels. The only previous study of a comparable magnitude was the series of CHESS studies conducted by the EPA which have been widely criticized on a number of technical and methodological issues.

Currently, there is only one preliminary report from the Six Cities Study which is relevant to the issue of indoor air pollution [26]. This report covers a population of about 8,000 children from 6 to 10 years of age who were assembled into 12 cohorts over a three year period. Health effects data were collected by questionnaire completed by parents and from simple spirometry tests conducted at schools. The authors reported that children from households with gas stoves had a greater history of respiratory illness before the age of 2 and significantly lower levels of forced expiratory volume in 1 second (FEV_1) and forced vital capacity (FVC) than children from households with electric stoves. The type of cooking stove was not significantly associated with two other measures of health effect, namely, history of bronchitis diagnosed by a physician and a history of respiratory illness in the last year. A significant association was reported between parental smoking and illness history. Parental smoking was also significantly associated with lung function residuals (FVC) but in the opposite direction from the expected difference. This unanticipated finding was not explained and until a resolution is found, it should serve as a warning that there may be faults in the data or the analytical procedures. Furthermore, it is surprising that a study, which acknowledges the weaknesses of the CHESS studies and the importance of integrated personal exposure data would report associations based upon extremely limited and non-personal indoor air sampling. In any case, the report is preliminary and too limited in scope for further review. Because of the potential importance of this study, it should be followed closely by all interested parties and, upon completion, will certainly be subjected to exhaustive review.

It has been noted by one of the principal investigators, Dr. Benjamin Ferris, that the preliminary results of this study are not appropriate for standards promulgation or revision. Dr. Ferris has identified a number of shortcomings including flaws in the sodium arsenite bubbler techniques for measuring NO_2, the limited amount of air quality data, and a lack of information on socioeconomic variables and has suggested that the data be treated with "circumspection." [27]

3.4 SUMMARY

There are numerous problems which hinder our ability to assess the adverse health effects of exposure to low levels of oxides of nitrogen and other indoor air pollutants. For example, the epidemiological data are limited and generally of poor quality; the human clinical data are not representative of actual exposure conditions and are contradictory; and the animal data are difficult to extrapolate to man. On the other hand, oxides of nitrogen at sufficiently elevated concentrations can cause adverse health effects and so epidemiologists and other public health professionals remain concerned about the potential adverse health effects of low level exposures.

In order to resolve this issue, a considerable amount of research is required. The most essential research need is a long-term prospective epidemiological study which should include monitoring of actual personal exposures and investigation of any related adverse health effects. Prior to undertaking such a study, research should be conducted to assess the validity of recently published and on-going epidemiological and toxicological studies. Research also should be conducted to improve the sampling and analytical methods for exposure monitoring and the diagnostic techniques for assessing adverse health effects.

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4. AIR INFILTRATION

4.1 OVERVIEW

An important factor that strongly influences levels of airborne contaminants to be found in a home is the rate of air infiltration, or simply stated, the rate at which outdoor air leaks into the home through various pathways. These air volumes, if cleaner than air found inside the home, can serve to dilute contaminants. Thus, it is generally true that higher rates of air infiltration are associated with lower indoor levels of airborne contaminants, and conversely, that lower rates are associated with higher levels.

The rate of air infiltration into a home at any given instant in time is an extremely sensitive and complex function of various interrelated factors. Based upon the findings of a comprehensive literature review, this chapter will attempt to define and discuss these factors. In addition, it will set the stage for subsequent chapters discussing current and future trends in air infiltration and the impact of infiltration rates on indoor air quality.

4.2 DEFINITIONS

According to ASHRAE, the American Society of Heating, Refrigerating, and Air Conditioning Engineers, infiltration is "air leakage through cracks and interstices, around windows and doors, and through floors and walls, into a building; its magnitude depends on the type of construction, workmanship, and condition of the building, and (it) cannot be effectively controlled by the occupants." In somewhat simpler terms, air infiltration into a building can be thought of in terms of the drafts one can sometimes feel indoors on a cold windy day even when all windows and doors are closed. These drafts occur because no typical building or home is airtight, and wind pressures and temperature differences produce driving forces that push air into a building through available leakage paths.

These same forces cause volumes of air to leave buildings through the process of "exfiltration". This process is exactly the opposite of infiltration and typically is in exactly the same magnitude such that the amount of air leaking into a building on one or more sides equals the amount leaving on others.

Some authors in the literature refer to infiltration as "air leakage", which is quite acceptable, or as "natural ventilation", which is not so acceptable. Although air infiltration has natural causes and can be referred to as natural air infiltration, the phrase "natural ventilation" in this country usually refers to intentional displacement of air through specified openings such as windows, doors, and ventilators without assistance from fans. When fans are used, the term "mechanical ventilation" is more appropriately applied.

4.3 UNITS OF MEASURE

One of the most common sets of units used to denote a ventilation rate is in terms of cubic feet of air per minute, or "cfm" for short. It is especially convenient for use when one is describing the flow of air through a duct or through any other opening through which air flow is induced. Air infiltration or leakage may be described in cfm whenever one is referring to the total leakage rate into an internal building space or the rate through some specified component of the structure. Its equivalent in metric units is cubic meters of air per second (m^3/s).

There is another set of units that is commonly used for describing the total infiltration rate into a space; however, that allows more meaningful direct comparisons between rooms in a building or between entire buildings. This is sometimes called "air exchange" rate and has units of air changes per hour, or ACPH for short. A total air change rate of 1 per hour in a home, for example, means that one building volume of air enters and leaves internal spaces of the home each hour. If the structure has an internal volume of 15,000 cubic feet, then that is how much outdoor air passes through in an hour.

4.4 MEASUREMENT TECHNIQUES

4.4.1 Descriptions

The most commonly utilized method to measure the natural air infiltration rate in an internal space of a structure involves addition of a known amount of tracer gas to the air of the space and measurement of the rate of decay of gas concentration as a function of time. If the infiltration rate is constant, and if the tracer gas is initially well-mixed with the air of the space, the decay will be exponential and will be characterized by the equation [15, 77, 164, 192,]:

$$C_2 = C_1 e^{-I (t_2 - t_1)}$$

where:

C_2 = tracer gas concentration at time = t_2 ($t_2 > t_1$)

C_1 = tracer gas concentration at time = t_1

t = time, hours

I = infiltration rate, air changes per hour (ACPH)

The usual procedure is for the gas concentration data to be plotted as a function of time on semilog paper. If the measurement technique has been conducted properly, the data will yield a straight line, and the slope of the line will indicate the infiltration rate.

Researchers over the years have utilized a number of different tracer gases and techniques for their dispersal and measurement. Among the gases have been radioactive krypton-85, xenon-133, argon-41, and bromine-82[62, 100, 161], and non-radioactive gases such as carbon dioxide[62, 141], hydrogen [62, 210], helium[15, 58, 59, 62, 77, 130, 182, 196, 283], water vapor[62, 157], tertiary butyl hypochlorite[62, 199], ethane[59, 88], carbon monoxide[115, 229], nitrous oxide[66, 119, 165], trichloroethane[203], methane[174, 316, 317], and sulfur hexafluoride[37, 118, 125, 134, 163, 165, 167, 205, 219, 231, 236, 298, 302]. Sulfur hexafluoride is probably the most popular today, but helium and nitrous oxide are still in common use.

Since results from tracer gas measurements can vary with changes in environmental conditions, and such changes may occur often, researchers have also developed a procedure for measuring air leakage under fixed conditions. Called the pressurization/depressurization method, it involves temporarily sealing a simple fan-in-a-duct assembly into a window or door of a structure and measuring the air velocity and flow-rate in the duct when a fixed pressure drop is maintained across the structure wall [35, 37, 51, 119, 120, 124, 125, 137, 165, 167, 189, 253, 258, 275, 291, 298].

Results of the procedure have been most useful for allowing relative comparisons of the leakiness of various structures, for identifying individual leakage paths, for quantifying the effectiveness of methods to seal leakage paths, and for defining the relative contribution of leakage paths to overall totals.

Analogous pressure difference procedures have also been utilized to measure the leakage through individual subelements of a building. ASTM Standard Method of Test E 283 [13], for example, has been used to develop air leakage standards for exterior doors, windows, and curtain walls. Houghten and his co-workers [153, 154, 155, 156] used the approach for similar investigations in the 1920's. A recent study [298] concentrated on the permeability of building materials.

Within the last few years, studies have also been undertaken to develop less expensive or more easily applied methods to identify leakage paths and/or measure air leakage. Card et al. [53] have reported on an "infrasonic" method of measuring air leakage that uses a motor-driven bellows-like source within the building to generate sinusoidaly varying volumetric flows. The resulting pressure variations are measured using a microphone-like sensor having an electronic signal processor. Keast [183] investigated the use of sound to locate leakage paths in a building.

4.4.2 Limitations of Measurement Methods

Due to the requirement that the tracer gas must be uniformly distributed within the structure before valid gas concentration decay measurements can be made, the tracer gas technique for infiltration rate measurement is generally limited to relatively small structures [233]. In addition, it has not yet been developed to the point to allow simultaneous measurement of the flows between rooms in a structure and of the infiltration and exfiltration rates within each room [233]. Thus, it is possible to determine the overall infiltration rate for a suite of rooms in a house, but it is not always possible to characterize accurately the flows into and out of individual rooms or spaces more or less open to each other. Although work has been done in this area [19, 20, 77, 101, 151, 263, 266], further efforts have been recommended [233].

Another potential problem with the method is that there is currently no standard method of infiltration rate measurement, although the American Society of Testing and Materials has been working towards this end. Not only can differences in gas sampling methods possibly affect results [163], but different tracer gases may give different answers even when used simultaneously. Howard [160] found that nitrous oxide and oxygen gave similar results, but that hydrogen gave significantly larger values for infiltration than nitrous oxide. Hunt and Burch [163] found that there were about 18 percent differences between results given by sulfur hexafluoride and helium and that the differences were not systematic. Hopefully, this latter problem area will be resolved by a soon-to-be-published paper [122] comparing tracer gases.

Results of the tracer gas method may also be affected by inaccuracies resulting from the gas sampling and concentration measurement equipment. Hunt and his co-workers [163, 164], for example, discuss instrument drift, concentration measurement errors, and inaccuracies resulting from non-uniform mixing of tracer gas and air. Nevertheless, Sherman and Grimsrud [260] suggest the method has a 90% to 95% accuracy.

There are a number of problem areas with the pressurization/depressurization technique also. As above, one has to do with the lack of a standardized procedure. Another has to do with the fact that the method imposes a rather uniform pressure gradient on the walls of a house while natural forces do not [233]. In direct consequence, measures of air leakage using the method may not produce results which can define building performance under natural conditions. Although Caffey [51] claims that the natural air infiltration rate in a home can be computed from pressurization/depressurization measurements simply by dividing the latter rates by a factor between 3.5 and 4.5, and Grimsrud and associates [119] have suggested a relationship for heavily shielded structures, others [125, 167] have found no good correlation between results. Finally, it is noted that some researchers have based their conclusions on measurements made at a single inside-outside pressure difference. Hunt, in discussions following presentations of References[275] and[291], has shown that results obtained [165] at different pressure differences may lead to different conclusions.

4.5 INFLUENTIAL FACTORS

As noted previously, the air infiltration rate into a home is a complex function of numerous interrelated factors. In the following, most if not all of these will be identified and discussed in the context of the difficulties inherent in their characterization.

4.5.1 Quality of Workmanship

The quality of workmanship (or "building quality") refers to the care taken during construction to minimize the size of air gaps between individual components of a building. Given two buildings that are otherwise identical, it is somewhat self-evident that the one built more "tightly" is prone to experience lower air infiltration rates.

The difficulty of characterizing a building in terms of its quality of construction has stymied the efforts of many researchers attempting to develop generalized methods of predicting air infiltration rates in homes. Although definition of quality may ultimately be practical for existing homes through use of the pressurization/depressurization method described above [233], it is unlikely that designers will ever be in a position to judge whether a home will be "loose", or "tight", or somewhere in between before it is built, and to assign some sort of quantitative measure to their finding.

4.5.2 Materials of Construction

Different types of building subcomponents, such as windows and doors, and different types of construction materials or techniques are typically associated with varying rates of air leakage. ASHRAE [10], for example, references specifications that permit the leakage rate though cracks around windows and doors to range from 0.375 to 1.5 cfm/ft of crack depending upon the type of unit. Various tables show the effect of different wall materials, wall thicknesses, wall coatings, weatherstripping, caulking, etc. on leakage rates. One particular table, and work by Houghton and his associates [153], demonstrate how leakage rates can vary not only with materials of construction but with quality of fit for double-hung windows.

An interesting note is that the materials and quality of construction may vary from region to region depending upon the particular climate. Grimsrud and co-workers [119] observed that homes in the San Francisco Bay area tend to be loosely constructed as a result of the mild climate. Keast [183] was unable to find interested members of the National Home Improvement Council (NHIC) in Houston and Los Angeles when trying to find contractors willing to test his acoustic method for identifying leakage paths. A NHIC affiliate in Houston explained that there was no significant market for energy conservation products and services in those warmer cities (in 1978), since heating requirements are small, and electric rates for air conditioning are one-third to one-half of those in the northeastern part of the country. In contrast, Keast apparently had little difficulty locating cooperative contractors in Boston and Washington, D.C., and the contractors found the method useful in convincing homeowners of the need for repair work to control infiltration.

4.5.3 Condition of Structure

Although a proper study of the subject has never been conducted, there is every reason to believe that the condition of a structure impacts infiltration rates and that the condition can change with time. It is rather self-evident that weatherstripping can wear out, caulking and mortar may deteriorate, wood may split or warp, and that other changes with time may influence the size and distribution of leakage paths and ultimately the air infiltration rate experienced.

4.5.4 Wind Effects and Influencing Factors

Air flow over or around a building due to wind provides a very important driving force for air infiltration. On the windward side(s) of a building, wind pressures tend to be positive and generally result in an inflow of air through available leakage paths. On the leeward side(s), pressures are apt to be negative and will promote air outflow. Obviously, stronger winds generally provide greater driving forces [10].

Numerous studies have attempted to relate external wind velocity to measured rates of natural air infiltration in homes with varied success, even when numerous other influencing factors have been taken into account. One reason for this involves the fact that the effect of wind pressures is itself a function of many variables such as size and location of leakage paths relative to the wind direction, presence of other structures or barriers to flow in the immediate vicinity, and presence of interior barriers to flow.

It would probably be rare to find a home that had the sizes and locations of leakage paths equally distributed among all four sides, especially since few homes are square. Thus, some deliberation on the subject reveals that changes in the direction of the wind, as well as changes in the wind velocity, have the potential to affect infiltration rates. Blomsterberg and Harrje [37] demonstrate clearly with a model that ventilation rates would be highest when openings are concentrated low on the windward side of a building and high on the leeward side, since wind effects would be enhanced by temperature difference effects (see below). Lowest ventilation rates were achieved when openings of equal total area were all located on the windward side. Although wind forces tried to force air into all openings, there were no outlets and the wind effect tended to cancel out. Others [88, 196, 205] have suggested or shown that infiltration rates tend to be lower when the wind impacts the narrow end of a home than when it impacts broadside, or have otherwise shown dependence on wind direction.

Interior barriers to flow include walls, floors, ceilings, closed doors, and similar obstructions that retard the movement of infiltrating air from the windward side of a building to the leeward side. They can essentially cause a buildup in internal pressure that reduces the pressure difference across the exterior wall(s) and thereby reduces the infiltration rate. Most researchers of infiltration rates try to negate the influence of this factor on measurements by performing experiments with all interior doors of the home open. Thus, there is scant data currently available on the impact of one or more closed interior doors, and available infiltration rate prediction methods cannot account for their effect.

Another complicating factor referred to above addresses the finding that the wind pressures acting on a home cannot always be simply estimated from knowledge of wind velocities in the area. The efforts of numerous researchers in the past are limited in value because they utilized wind data from distant meteorological stations often located at airports in relatively open country, or they measured wind speeds on-site above rooftop levels. Thus, they did not consider that the actual wind forces acting on the walls of the building would be strongly influenced by the surface roughness of the terrain, the presence of trees, and the presence of other buildings. Unequal distributions of such external barriers can increase the impact of wind direction on infiltration rate predictions.

Kelnhofer [185] has demonstrated that even a single neighboring building can increase or decrease infiltration rates depending on its size, shape, and location relative to the wind. Lee and co-workers [198] have studied the effects of a large neighboring group of buildings in this regard. Grimsrud and associates [119] found a significant difference between measured pressure differences and those expected due to sheltering effects. Mattingly and Peters [211] and Buckley and co-workers [45] studied the effect of trees, with the latter finding that trees on the windward side of an otherwise unprotected building can lower the infiltration rate experienced by as much as 45%.

Hill and Kusuda [141], in a frequently cited paper, postulated that air change through window cracks is primarily a result of a pulsation process, and the result is complicated by the fact that air can flow into and out of a room simultaneously. This finding suggests that the nature of fluctuating winds may affect infiltration rates.

4.5.5 Temperature Effects

It is not uncommon for the interior of a building to have a termperature higher than that of the outdoors. Under such circumstances, differences in air density can cause a chimney or stack effect. Warm air rises and attempts to escape through the upper areas of the building, while colder air moves inward at lower levels to replace it. The reverse may occur when the indoor temperature is lower than outside. The magnitude of the effect is minimally a function of the indoor-outdoor temperature difference, the height of the building, the presence of internal barriers to flow, the presence of chimneys and vents, and the size and location of leakage paths.

The influence of the indoor-outdoor temperature difference is somewhat self-evident. Greater differences produce greater air density differences and greater pressure differences across the building enclosure due to the chimney effect. An important concept to understand when thermal forces act alone is that a neutral pressure level (NPL) will exist where there is no pressure difference between inside and outside. At other levels, the pressure difference across an exterior wall will depend upon vertical distance from the NPL as well as the difference in air densities between indoor and outdoor air [10]. This directly leads to the finding that thermal effects are usually greater in taller buildings than shorter ones. Thus, thermal effects might be greater in a two-story home than in a single-story dwelling.

In the case of wind-induced effects, it was noted that internal barriers to air flow may influence infiltration rates. The same concept also applies to temperature-induced effects. The floors and ceilings between levels can impede the flow of air and lead to lower pressure differences than would occur if the building did not have internal partitions. Malik [205], for example, clearly demonstrated that the opening of an interior basement door enhanced the stack effect and thereby the infiltration rate in a townhouse.

Chimneys and vents to the outdoors may provide direct paths for vertical air movement in a home. For houses, the NPL is usually above midheight, and a chimney will raise the NPL as outdoor temperature drops [10].

The size and relative location of leakage paths, as noted previously, also play a role if they are not equally distributed. The stack effect more or less requires leakage paths to exist both at upper and lower levels of a building.

Burch and Hunt [47] found an interesting effect when the attic and crawl space ceiling of one house were insulated. The insulation caused a significant increase in the temperature difference between the living space and the spaces immediately above and below. This in turn caused a small but systematic increase in infiltration.

Personnel at the Institute of Gas Technology have reported the possibility that ice and snow might cover or otherwise reduce the size of cracks and the like. This would be somewhat of an indirect temperature effect.

4.5.6 Humidity and Other Weather Effects

The impact of relative humidity on infiltration rates has usually been ignored by researchers in the past. Luck and Nelson [203], however, discovered a possible relationship between humidity and infiltration rate that makes sense. They hypothesized that swelling or shrinking of wood with changes in humidity can affect crack dimensions, and found a correlation between humidity levels and infiltration rates. In addition, they presented a calculation that demonstrates crack dimensions around a normal double-hung window may be reduced by about 50% when the relative humidity increased from 20% to 40%. Others [233] have noted that solar radiation heating the outside of buildings may significantly affect the crack size around metal window frames.

Stricker [275] studied 24 homes and found that homes exhibiting high humidity were generally tighter than others. Instead of attributing the tightness to high humidity, however, he essentially assumed that the tightness was causing the high humidity. It is possible that both viewpoints are partially correct.

4.5.7 Heating System Effects

It has often been shown [15, 16, 88, 165, 174, 175, 196, 205, 231, 283, 298] that the type of heating system used in a home can affect the air infiltration rate. Homes using fossil fuels such as gas and oil require significant quantities of air, frequently extracted from living spaces and/or basements, for combustion in furnaces. Janssen and Bonne [175] have noted that stack air flow must come partly from increased infiltration and partly from decreased exfiltration. They claim that these effects are equal under many conditions and that only 50 percent of the flow can be charged to increased infiltration. They also note, however, that measurements have shown that a 70 percent figure is a "good average" for the amount chargeable to infiltration.

A complicating factor is that the overall effect is partially a function of the length of time of furnace operation. Infiltration rates will increase or decrease depending on whether a furnace is on or off. Another such factor involves the number, size, and location of leakage paths to basements. A furnace will have less effect on living spaces if it can draw more of its required air supply directly into the basement from outside.

4.5.8 Leakage Paths

The influence of leakage path size and location has been discussed above. To complete the picture, it is also advantageous to describe the nature of leakage paths typically found in a home.

Caffey [51] found 12 major areas of leakage when performing pressurization/ depressurization tests on 50 homes. The average contribution of each area to the total infiltration rate was found to be as follows:

Leakage Area	Percent Contribution
Soleplate; baseboard area of exterior wall	25
Electrical wall outlet openings	20
Duct systems	14
Exterior windows	12
Range vent	5
Fireplace	5
Recessed spot lights	5
Exterior doors	5
Dryer vent	3
Sliding glass door	2
Bath vent	1
Other	3

Tamura [291] utilized a similar measurement method on six houses and found that the leakage values of windows and doors with storm units contribute from 15 to 24 percent of overall leakage values. In addition, he found that leakage values of exterior walls with stucco finish are significantly lower than those of masonry or a combination of masonry and aluminum siding or asbestos shingles. Leakage rates through ceilings ranged from 5 to 65 percent of totals with an average 31 percent. Rates for outside walls ranged from 15 to 77 percent of totals with an average of 48 percent.

Using a tracer gas technique, Hunt and Burch [163] saw only a slight decrease in infiltration rate when ducts to kitchen, bathroom, and clothes dryer fans were sealed. The results agreed roughly with Caffey's findings on the influence of these vents. These researchers also found no systematic further decrease in infiltration rate when doors were sealed, and due to the nature of their experiments, noted the possibility that door cracks and duct openings play a comparatively small role in air exchange under conditions of very low wind velocity. Hunt and co-workers also found that storm windows had little beneficial effect in mobile homes [165] and that windows, doors, and fireplaces accounted for no more than 12% to 18% of leakage in one apartment studied [167].

Teitsma and Peavy [295] estimated that sealing off jalousie windows in a mobile home reduced leakage by about 18%. Coblentz and Achenback [59] found that the infiltration rate in one home decreased on the average from 0.79 to 0.58 ACPH when kitchen and bathroom vents were closed.

Treado and co-workers [298] utilized the pressurization/depressurization method to study a townhouse with the following results.

Leakage area	Percent Contribution
Exterior wall (w/o ceiling interface)	27.9
Ceiling (w/o wall interface)	12.3
Party wall	4.5
Windows and doors	4.5
Electrical outlets	4.4
Floor/wall interface	23.1
Others	23.3
	100.0

Sinden [264] also discusses leakage paths in a townhouse and in wooden homes in general. He specifically mentions the flue, the soleplate area, the open shaft around the metal flue in the attic, a variable gap between the masonry party wall and the wooden structure of the house in the attic, holes around pipes, wires and other fixtures, gaps between gypsum board and framing, gaps around heating ducts, windows, doors, and outdoor joints.

Shepherd and Gerharter [258] systematically discuss the topic in detail. To the leakage paths noted above, they add laundry chutes, mail slots, basement floor drains, sewer pipe penetrations, garage-house connections, gaps around window type air-conditioners, doorbells, thermostats and smoke alarms, gaps around bathtubs and shower stalls, stair steps and risers over unconditioned spaces, leaky fireplace dampers, and others.

Grimsrud and associates [119] and other researchers have discussed the impact of leaky ductwork on infiltration rates. In a California house, it led to significant cross-flow between the attic, living space, and crawl space.

4.5.9 User Influences

For all practical purposes, the rate of infiltration into a home includes any incremental air exchange due to the opening and closing of external doors [88], the operation of kitchen and bathroom exhaust fans, the operation of heating systems (see above), and the opening and closing of interior doors such as to change the impact of interior barriers to flow (see above). It is evident, therefore, that the habits of occupants can affect infiltration rates, and that two otherwise identical homes can experience different air infiltration rates due solely to differences in the habits of residents. Similarly, it is evident that unoccupied structures, with some exceptions, are likely to have lower rates than those that are occupied.

In order to understand the relationship between indoor air quality and air exchange rates in a home, it is necessary to consider the fact that the <u>total</u> ventilation rate is the sum of the air infiltration rate and air exchange associated with natural ventilation, i.e., the intentional opening of exterior windows and doors by residents. With a depressurization type measurement, Hunt [167] demonstrated that the opening of windows only a quarter of an inch doubled the air leakage rate in an apartment. Dick and Thomas [77] found that air exchange rate increases on the order of one change per hour can be expected during the heating season due to occupancy (for homes in England in 1948 to 1950). They demonstrated [78] a linear relationship between the number of windows open and the mean outdoor temperature in another study of homes without central heating and also observed that higher wind speeds resulted in fewer open windows.

In a 1977 paper, Brundrett [44] reported upon the modern English housewife's window-opening behavior and found wide differences between families. Important factors were the size of the family, whether the housewife was normally at home during the day, and weather conditions. Homes with working wives had only half the open windows on the average than of those who stayed at home. Similarly, larger families tended to have more open windows. In summer, window-openings were primarily linked to mean daily temperature. In winter, the controlling factor in the

the locale studied was the moisture level in the external air. The most popular rooms to have open windows were bedrooms. Kitchen windows were more apt to be open in the coldest weather for the probable purposes of removing smoke, excess heat, and cooking smells.

Hunt and co-workers [165] studied a mobile home and found under certain conditions that one open exterior door would increase the ventilation rate to 2-4 ACPH, about 4 to 8 times the natural infiltration rate. Malik [205], after noting some ambiguities in his data, theorized that occupants are more likely to close windows and doors carelessly during milder weather than would be the case in winter. In this regard, Houghten's work [153] clearly shows that unlocked double-hung windows leak substantially more than locked ones.

4.6 MEASURED RATES OF INFILTRATION

A selective review of the ranges of infiltration rates measuredin North American homes over the years sets the stage for a demonstration of the relative contributions and impacts of the influential factors discussed above. In addition, it forms the basis of subsequent discussion relating air infiltration rate and/or total ventilation rate to measures of indoor air quality.

In one of the earlier studies Bahnfleth and co-workers [15, 16] examined two well-built homes with gas heat from the winter of 1954-1955 to the summer of 1956. The results showed that most but not all air change between the first and second stories of one home was upward during the heating season. Over a wide range of wind velocities and indoor-outdoor temperature differences, the infiltration rate in one home ranged from 0.16 to 0.43 ACPH. Rates in the kitchen were comparable. In the second home, rates averaged from 0.26 to 0.80 ACPH. The authors noted that the home better sheltered by trees and other buildings had smaller infiltration rates under similar environmental conditions. They also noted the possibility that leaves on trees in the summer increase the sheltering effect. In cold weather, the heating plant chimney of one home was seen to be an important factor. The combined effect of the chimney and bare trees in winter appeared to increase infiltration rates by 0.1 ACPH within living spaces. In actuality, however, the chimney had flow equal to 0.8 to 1.0 ACPH for one house, with air being mostly drawn through leakage paths to the basement and also from the first floor. In the other house, chimney flow was 0.27 ACPH and did not disrupt upward flow from the basement to the first floor. At zero wind and temperature difference, air change rates respectively were 0.12 and 0.19 ACPH.

Blomsterberg and Harrje [37] note that it is often quite simple to drastically reduce air leakage in leaky houses using the depressurization method to identify leakage paths. In a number of townhouses, the average infiltration rate dropped from 0.7 ACPH to 0.4 ACPH after major leaks were sealed. Of particular importance were paths leading from the basement to the attic.

Burch and Hunt [47], after extensive retrofitting of a wood-frame residence, found that summer infiltration rates ranged predominantly from 0.2 to 0.4 ACPH and were approximately one-half of typical winter values. Systematic attention to the sealing of air infiltration leakage paths produced only marginal reductions in air exchange rates. Their results indicate that a wind speed of 15 mph coupled with an indoor-outdoor temperature difference of 50°F would produce an infiltration rate of about 1.0 ACPH. Rates would be lower under less severe conditions. Unexplained by the authors is the indication in certain graphs that pre-retrofit infiltration rates were actually lower than post-retrofit rates for some conditions.

Caffey [51], using a somewhat unique and indirect method of estimating natural infiltration rates (one that may be error-prone) found that the average infiltration rate in a sample of 50 homes was 1.5 ACPH with an indoor-outdoor pressure difference equal to that caused by a 15 mph wind, and that 0.5 ACPH was a realistic goal achievable with a few changes in home building techniques. Retrofitting in one house reduced the rate from about 1.25 to 0.9 ACPH. A particularly tight home with a rate of 0.35 ACPH had exterior walls filled with urea-formaldehyde foam and exterior walls and ceilings innerlined with polyplastic film.

Coblentz and Achenback [59] studied ten electrically-heated houses considered representative of a majority of residential construction. Over a wide range of weather conditions, observed infiltration rates for these structures ranged from 0.23 to 1.14 ACPH with an average of 0.67 ACPH. When all rates were adjusted to a uniform indoor-outdoor temperature difference of 40°F and a 10 mph wind velocity, the range was 0.23 to 1.24 ACPH and the average was 0.64 ACPH. All the houses had storm sashes.

Elkins and Wensman [88] surveyed natural infiltration rates in two occupied, modern, tight homes over a one-year period. They found that rates may vary considerably on an hour-to-hour basis depending upon activities of occupants and changes in weather parameters. Average rates varied from 0.24 to 0.83 ACPH in a gas-fueled home and from 0.13 to 0.42 in an otherwise identical all-electric house with sealed chimney. On one particular afternoon, the all-electric home experienced an actual rate of only 0.066 ACPH.

Goldschmidt and Wilhelm [115] studied infiltration rates in two unoccupied mobile homes free from obstructions to wind by terrain or other buildings. A home with caulking used at all joints had rates ranging from 0.079 to 1.030 ACPH during the summer with a rate of 0.91 ACPH at typical design conditions. At winter design conditions, the rate was 1.53 ACPH. A home without caulking but with continuous sheathing board had rates of 0.061 to 0.549 in summer with a rate of 0.46 ACPH at design conditions. In winter, the rate at design conditions was 0.83 ACPH.

Grimsrud and co-workers [119] studied a small, three-bedroom California house. Infiltration rates measured ranged up to 1.25 ACPH although there was considerable shielding of the house from wind. The lowest natural rates measured appear to have been on the order of 0.35 ACPH. Six homes were studied in another investigation [120]. Two with polyethylene vapor barriers and other components designed to limit energy losses respectively had measured air infiltration rates ranging from 0.10 to 0.12 ACPH and 0.08 to 0.13 ACPH. Another house with vapor barrier had 0.31 to 0.42 ACPH while more typical homes in California had rates of 0.15 to 0.61, 0.51 to 0.69, and 0.64 to 1.36 during the limited testing period.

Grot and Clark [125] investigated the air leakage characteristics of approximately 266 dwellings occupied by low-income households in 14 cities in all major climatic zones of the U.S. Approximately 68% of the buildings were frame, 16% masonry, and 11% masonry-veneer. The age distribution was fairly uniform from 10 to 80 years with the median age being about 45 years. About 62% used natural gas for space heating, 20% oil, 14% propane, 3% electricity, and 1% kerosene. Of a total of 1048 measurements, about 19% were below 0.5 ACPH, 40% were between 0.5 and 1.0 ACPH, 20% between 1.0 and 1.5 ACPH, and 20% greater then 2.0 ACPH. Weatherization measures considered cost-effective for particular homes reduced fan-induced infiltration rates by 5 to 97% depending on the specific actions taken. The average reduction was about 34.4%. For all measurements, the geometric mean natural infiltration rate was 0.86 and the arithmetic average was 1.12 before weatherization.

Hunt and co-workers [165] studied a mobile home placed in an environmental chamber. Infiltration rates under varying conditions ranged from about 0.3 to 0.8 ACPH, of which about 0.2 ACPH on the average was attributed to continuous furnace fan operation. Installation of storm windows did not have an appreciable effect on natural air infiltration rates. Under pressurization, noticeable leakage was observed all around the perimeter of the structure where the base trim meets the external aluminum wall covering.

Hunt et al. also studied infiltration in Chicago apartment houses [167] and in a 4-bedroom townhouse [163] placed in an environmental chamber. The apartment house data somewhat suggested that top floor apartments had greater infiltration rates than units on lower floors. Individual rates measured in top floor apartments in two tenement buildings and in a more modern suburban structure were 1.25, 1.6, and 0.99 ACPH respectively. On lower floors, a tenement apartment had a rate of 0.83 while a newer unit had a rate of 0.76. The effect of sealing windows, doors, and fireplaces was discussed previously.

Townhouse experiments addressed the influence of indoor-outdoor temperature differences in the absense of wind forces. Infiltration rates varied from about 0.16 to 0.82 ACPH as the difference increased from 9.6°F to 52.3°F. The sealing of ducts to kitchen, bathroom, and clothes dryer fans resulted in only a slight decrease in infiltration rate, as did sealing of doors.

Janssen and co-workers [174] looked at contemporary residential structures in three different climates. In a Minneapolis tri-level, rates of 0.49 and 1.07 ACPH were measured with the furnace on. These dropped to 0.46 and 0.95 ACPH respectively with the furnace off. Five Denver homes had rates from 0.41 to 1.19 with the furnaces on and 0.41 to 0.97 with them off. In five Kansas homes, comparable ranges were 0.47 to 0.75 and 0.42 to 0.57. Based upon observations, the authors concluded that a strong gusty wind and an open fireplace damper can double the infiltration rate. Some general observations, that may or may not be completely valid, were that contemporary houses: 1) exhibit rates of 0.4 to 0.6 ACPH if equipped with double glass windows; 2) exhibit about 0.75 ACPH with single glass windows; and 3) exhibit about 1.0 ACPH with poor fitting doors and windows.

Laschober and Healy [196] statistically analyzed data from infiltration rate measurements in two split level homes. In one somewhat unusually designed research house, the rate varied from 0.32 to 2.67 ACPH, with higher values being clearly associated with quite severe weather conditions. In a more typical structure, the rate varied between 0.23 and 1.79 ACPH. Gas furnace operation was estimated to contribute 0.14 to 0.16 ACPH to results in the second house.

While investigating the effect of humidity on infiltration rates, Luck and Nelson [203] measured infiltration rates in a small one-story home near Minneapolis. During the heating season, these varied from 0.48 to 1.60 ACPH. The highest rate occurred with a 20 mph wind velocity and 82°F indoor-outdoor temperature difference. The lowest was with a 5 mph wind and a 35°F temperature difference.

With wind speeds slower than 6 mph, and with an indoor-outdoor temperature difference of 43.4°F, Malik [205] determined infiltration rates of 0.48 and 0.54 ACPH in two townhouses. Detailed analysis of the home with 0.54 ACPH indicated that about 0.2 ACPH was due to the stack effect and that continuous gas-furnace operation would contribute 0.24 ACPH. At these low wind speeds, opening of an interior basement door would increase the rate by 0.1 ACPH and there would be an additional increase of 0.53 ACPH if the front door was kept open. Observations made at higher wind speeds in one townhouse demonstrated: 1) the effect of the wind appears to be partially due to greater gas consumption at higher speeds; 2) the impact of furnace firing on the infiltration rate appears to be greater since windy weather may increase the entrainment of house air with combustion products on their way out of the flue; 3) there is a complex interaction between wind and temperature effects such that the magnitudes of the effects taken individually are not always additive.

Prado and co-workers [229] studied a new mobile home under a variety of conditions. Infiltration rates varied from 0.57 to 2.69 ACPH in the living area depending upon wind speed, temperature difference, and air-conditioning and furnace blower operations.

Tamura and Wilson [283] studied two tight one-story houses located in Ottawa, Canada. During two winters, infiltration rates varied from 0.25 to 0.41 ACPH in one house and in the first winter from 0.37 to 0.63 ACPH in the other over a wide range of environmental conditions. During the second winter, this latter house had its windows sealed with tape and experienced 0.33 to 0.57 ACPH, showing about a 10% decrease. During one summer the rates in the houses were respectively 0.07 to 0.16 ACPH and 0.11 to 0.23 ACPH. During summer, rates varied approximately linearly with wind velocity. During winter, they were influenced by wind and stack action. The rate under the combined influence of these forces was again less than the sum of rates due to them being active independently.

Treado and co-workers [298] studied a 3-bedroom townhouse. When wind speeds varied from 2.0 to 3.0 mph, temperature differences varied from -6.4 to 41.7°F, and the furnace blower was cycled on and off, the air infiltration rate ranged from 0.13 to 0.62 ACPH. Blower operation caused an average increase of 0.11 ACPH or about 20%.

4.7 INFILTRATION RATE ESTIMATION MODELS

4.7.1 Previous Studies

There have been numerous attempts in the past to develop empirical relationships between infiltration rates into homes and the important factors that influence rates. In addition, various physical models have been developed based on mathematical representations of the various phenomena that take place, and attempts have been made to estimate natural air infiltration rates from data obtained from pressurization/depressurization measurements. In general, none can be considered "finished" or widely applicable at present, although one or more recent attempts may eventually lead to viable estimation procedures after further development and/or validation efforts.

4.7.2 Empirical Models

Ross and Grimsrud [233] provide an excellent contemporary review of 12 papers presenting empirical relationships derived from experimentally obtained data. A common example is:

$$INF = A + B \cdot W + C \cdot \Delta T$$

where INF is the infiltration rate, W is the wind speed, ΔT represents the indoor-outdoor temperature difference, and A, B and C are constants derived from regression analysis. Other relationships reported in the literature are similar but more complex, with terms included to address the number of open windows, wind direction, interaction between wind and thermal effects, type of heating system, humidity, heating fuel consumption, fraction of time various doors are open, and so on.

Despite various efforts to enhance the overall understanding of infiltration rate associated phenomena in residences, the basic approach is not very likely to result in a widely applicable procedure for predicting air exchange rates, although Peterson [226] has made a crude yet logical attempt in this direction. Harris hinted at one reason for the problem in discussion following the presentation of a paper by Coblentz and Achenbach [59] when he noted that the constants in regression analysis expressions are structure-related and determined primarily by the quality of construction. This suggests that an infiltration rate model determined for one house cannot be used with the same constants for another house.

In actuality, the basic problem with the approach is likely to be more fundamental in nature. Besides quality of construction, these expressions are generally incapable of addressing differences in materials of construction and their infinite number of combinations, differences in the nature and distribution of leakage pathways between homes, differences in the nature and configuration of interior and exterior barriers to air flow, and so forth.

In an unpublished document appended to Reference 233, Sepsy and his coworkers statistically analyzed the validity of these linear models with the ultimate objective of developing a generalized, unified model for any residence. They eventually gave up, stating that although these models as a group are essentially equal in their ability to predict air infiltration, they fail to predict consistently accurate values. A paper by Reeves, Sepsy, and others [231] summarizes their findings.

About the only consistent finding among modellers using these approaches has been the indication that typical homes experience an infiltration rate on the order of 0.1 ACPH even when the wind speed and indoor-outdoor temperature differences are zero [231]. A fully satisfactory explanation for this finding has not been proposed to date, but it appears to be some effect attributable to the tracer gas decay method.

4.7.3 Physical Models

The more or less "standard" physical model used to compute expected air infiltration in a building is the crack method described in Chapter 21 of the 1977 ASHRAE Handbook of Fundamentals [10] and in Section A4 of the 1970 IVHE Guide Book A [170]. Derived from basic theory, the method has usually been applied for the purpose of sizing heating and cooling equipment. It was developed at a time when fuel was inexpensive and gross approximations of infiltration would suffice [177]. Thus, it is not surprising that numerous authors have discovered and pointed out deficiencies in the method.

Hunt [167] applied the crack method to a Chicago apartment and found it over-predicted the infiltration rate (as determined with a tracer gas) by over 400%. Prado and co-workers [229] tried it and concluded that it "unfortunately does not apply too well to mobile homes." Bahnfleth et al. [16] found fairly good agreement between computed and measured results but implied that the agreement was somewhat accidental since the agreement was a result of over-estimating the effect of wind forces and neglecting the effect of temperature difference forces.

Tamura and Wilson [283] considered good agreement in one case to have been mainly due to a "fortuitous" selection of leakage coefficients. In another case, it was clear that the crack method was in error by an amount depending upon the temperature difference between inside and outside and on furnace action. Janssen and associates [177] compared measured and computed results for 4 homes and found varying degrees of agreement. They concluded that the model is adequate for sizing equipment but not for assessing indoor pollution problems. Laschober and Healy [196] compared measured and crack method results and found considerable variation. Lee and associates [198] pointed out that the main assumption made in guidebooks vis-a-vis pressure differences caused by wind may result in considerable error. Stricker [275] found that the measurement equivalent leakage areas in three homes were 2.5 to 3 times greater than the leakage predicted by the ASHRAE crackage method. Similar adverse findings [16, 59, 177, 196] were found for the alternate and less sophisticated "air change" method presented by ASHRAE [10].

With respect to the crack method, ASHRAE [10] itself notes that its accuracy for design load calculation "is restricted by the limited data on air leakage characteristics of components and by the difficulty of estimating pressure differences under appropriate design conditions of temperature and wind. Specific air leakage data are available for a variety of components used in buildings, but differences develop between components as tested and as installed or constructed. The major limitation, however, is in estimating the appropriate pressure differences." It goes on to note that a "basic problem in using the air change method is to define the proper (building or room) volume to be used, particularly for high ceiling rooms. Experience and judgement are required for good estimates."

Much recent work has involved the development of more rigorously derived physical models. Tamura [294] presents one method that gives results agreeing quite well with measured values, but notes a number of areas in which further work is necessary to better define model input data and/or to further check the validity of the model. Cole, et al. [65], Macriss, et al. [208a], Etheridge and Alexander [101], Sepsy with Reeves and co-workers [231, 233], Sherman and Grimsrud [260] and others [119, 185, 211] present models essentially at similar stages of development. Some of these models require input data derived from pressurization/depressurization experiments, and therefore are not completely analytical in nature.

4.8 CONCLUSIONS

This review leads to a number of conclusions concerning the current stage of knowledge vis-a-vis air infiltration phenomena in North American homes. By individual subject area, these include the following statements.

Measurement Methods

1. The use of tracer gas decay technique currently represents a viable means to measure natural air infiltration rates in homes. The method itself is in an advanced state of development, but further efforts are necessary for standardization, for understanding the relative behavior of different tracer gases, and for improvements permitting evaluation of multi-chamber effects.

2. The pressurization/depressurization method of measuring induced air infiltration rates permits comparison of the relative "leakiness" of homes under fixed, albeit somewhat unnatural conditions. In addition, application of the method can further an understanding of the relative contributions of leakage pathways. The method would benefit from standardization and from further research directed toward relating results to natural infiltration rates. Contrary to the findings of some researchers, it does not appear that this relationship can be simply defined.

Influential Factors

3. The quality of workmanship applied in the construction of a home can significantly impact the infiltration rates subsequently experienced. This "quality" is currently undefinable in quantitative terms.

4. Different materials of construction are associated with different component-specific infiltration rates. There is reason to believe that the leakage rates through components measured in a laboratory vary from those experienced when the component is actually installed in a home.

5. It is likely that the infiltration rates experienced in a home will change with time as components deteriorate or otherwise vary from original specifications.

6. Air infiltration rates are most definitely a function of external wind speeds. The relationship is not well-defined, however, although considerable work has been done in this area. It is imperative for future researchers to pay special attention to the microclimate in the vicinity of homes and how it is impacted by external barriers to unrestricted air flow.

7. The nature, size, and distribution of leakage paths can affect air infiltration rates.

8. There is probably a complex relationship between wind velocity in the microclimate of a building, the external temperature, furnace operation, stack flow through chimneys, and air infiltration rates.

9. The amount of air infiltration chargeable to furnace operation will vary with the relative contribution of leakage paths to basements. A tight basement can lead to air being drawn from living spaces.

10. Little work has been done to define the impact of internal barriers to flow on infiltration rates. It would be interesting to determine the before- and after-impact of opening and closing interior doors on infiltration rates, particularly in the vicinity of kitchen areas.

11. Indoor-outdoor temperature differences influence infiltration rates through stack action. The magnitude of the effect is partially due to the presence and location of a neutral pressure level and numerous other factors.

12. Insulation of a home can indirectly impact air infiltration rates by changing indoor-outdoor temperature differences in spaces surrounding living areas.

13. Ice and snow may impact infiltration rates by temporarily plugging leakage pathways.

14. Although the subject has not been studied thoroughly, there are strong indications that infiltration rates may vary with humidity levels.

15. Heat causes most materials to expand. This leads to an indirect effect of temperature that has not been specifically addressed.

16. There are numerous potential leakage pathways in homes. Their relative importance from home to home will differ depending upon a variety of factors. In general, it does not appear that exterior windows and doors account for more than 25% (and probably less) of leakage.

17. The average homeowner would have difficulty in independently locating and sealing the major leakage paths in his particular home.

18. The total ventilation rate experienced by a home is a strong function of the habits of occupants. These can vary substantially.

19. Open windows and/or doors can substantially increase the total ventilation rate experienced.

20. There are indications that occupants are more likely to close windows and doors carelessly in milder weather than would be the case in winter.

Measured Rates of Infiltration

21. Infiltration rates measured in mild weather (summer) are generally substantially lower than those measured in winter.

22. It is not uncommon to find tight homes with infiltration rates on the order of a few (or less) tenths of an air change per hour under many circumstances. Similarly, there are loose homes that may experience 2.0 or more air changes per hour at a time. Most homes are somewhere in between, varying across a wide range as a function of environmental conditions.

Estimation Models

23. The ASHRAE crack and air change methods of estimating infiltration rates simply provide crude approximations. Actual rates may be less or greater than predicted rates depending on circumstances.

24. Empirical models presented in the literature are not widely applicable.

25. Significant progress has been made in the development of a physical model. Further work in this area is likely to result in a viable and accurate technique in the near future.

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5. TRENDS IN RESIDENTIAL AIR INFILTRATION

5.1 INTRODUCTION

As energy costs have continued to escalate, and spot shortages have occasionally been experienced, there has been increasing attention to the identification and implementation of methodologies for energy conservation. In the area of residential heating and cooling, this attention has been partially focused on the means to reduce air infiltration losses. It is well, therefore, to review briefly activities in this area, and to discuss them in the context of potential impacts on indoor air quality.

5.2 ENERGY CONSIDERATIONS

The average residential energy use pattern for 1970 was reported upon by Dole [1]. His analysis demonstrated that approximately 55 percent of primary residential energy consumption was attributable to space heating, 4.6 percent to air-conditioning, and the rest to water heating, refrigeration, freezing, lighting, cooking, and so forth.

According to data obtained from the DOE Energy Information Administration by the Office of Technology Assessment (OTA) in 1979 [2], Americans utilized 17.21 Quads* of energy in 1977 for residential purposes. OTA estimated that this amount accounted for approximately 23.2 percent of total national energy consumption. About 51 percent of the 17.21 Quads was attributed to space heating and 6.6 percent to cooling. Thus, there were only minor changes in use patterns between 1970 and 1977, and it is possible to estimate that roughly 13.3 percent of national energy consumption is currently devoted to residential heating and cooling. Based on available 1977 data, this amounts to some 9.9 Quads of energy in round figures.

Various estimates in the literature attribute space heating losses due to air infiltration as accounting from 20 to 40 percent of the total heating energy requirement. The percentage range for cooling energy losses is usually somewhat lower at 15 to 25 percent, or so. Thus, it is apparent that roughly 2 to 4 Quads of energy are currently lost each year due to infiltration of non-conditioned outdoor air into homes, and it becomes evident why this wastage, equivalent to 2.7 to 5.4 percent of national energy consumption, has been receiving considerable attention. To individuals uninformed of potential indoor air quality problems, energy conservation through reductions in air infiltration suggests a "painless" route not likely to require a noticeable change in lifestyle.

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*A Quad = 1 quadrillion Btu = 1.055 exajoule (EJ).

5.3 PERTINENT GOVERNMENT ACTIVITIES

In 1971, the President directed the Secretary of Housing and Urban Development (HUD) to reduce maximum permissible energy loss by "about one-third for a typical 1200-square-foot-home, and by even more for larger (federally insured) homes."[3] On July 12, 1973, the National Conference of States on Building Codes and Standards (NCSBCS), asked the National Bureau of Standards (NBS) to develop the basis for a performance-type standard for energy conservation in new buildings. Section 5.0.6 of this document addressed air leakage control and stated that "the natural (not mechanically forced) leakage of air between indoors and outdoors shall not exceed 0.7 air change per hour for one- and two-family dwellings and 0.5 air change per hour for all other buildings and mobile homes." Within a year of the publication of the revised document, HUD (in 1977) revised its 1973 Minimum Property Standards [4]. One result was to limit the infiltration rates in single-family residences to 0.7 air changes per hour or less [5]. Thus, the infiltration rate limit became a Federal regulation for housing built under HUD mortgage insurance and low-rent public housing programs.

One of the numerous provisions of the Energy Policy and Conservation Act (Public Law 94-163) enacted by Congress in 1975 encouraged the States to adopt mandatory thermal efficiency standards and insulation requirements for new buildings. The implementation of the legislative mandate led to the development of a Model Code by the NCSBCS under a contractual agreement with the DOE. This model building code reflected the technical provisions of ASHRAE Standard 90-75 [6] as discussed below, and has now been adopted in whole or part by 44 states [2].

In August of 1976, in response to the need to encourage greater conservation of depletable energy resources, Congress passed the Energy Conservation Standards for New Buildings Act of 1976 (42 U.S.C. 6831-6840). In direct response to Section 304 of the Act, the Department of Energy developed energy performance standards for new buildings after considerable research into the matter. On November 21, 1978, an Advance Notice of Proposed Rulemaking was published in the Federal Register, and in December of 1978, public meetings were held in Washington, Chicago, and San Francisco to solicit public comments. In all, 34 individuals testified at meetings and 186 written comments were submitted.

Based on the comments received and results obtained from ongoing research, the DOE revised its Building Energy Performance Standards (BEPS) and published a Proposed Rulemaking in the Federal Register [7] of November 28, 1979 with a request for further comments. A draft environmental impact statement was published [8] the same month. The preamble to BEPS at that time addressed the question of indoor air quality, and recognized the potential for conflict between energy conservation objectives which would reduce infiltration rates and the adverse impacts of indoor air pollutants. DOE noted it "has taken a cautious approach in dealing with this issue."

DOE's cautious approach was to design the standards so that no credit or penalty is given for the design of a building with lower or higher infiltration rates than what is typical. Thus, it felt justified in repeatedly stating that the standards are expected to have no effect on the indoor air quality of buildings constructed after the standards are implemented. Simultaneously, however, it warned that it "is presently developing approaches to evaluate the effects of different measures to reduce infiltration in single-family residential building designs.... These measures could reduce the average air infiltration rate to 0.1 air change per hour in a mild climate and 0.2 air change per hour in a colder climate." It was clear that DOE at this time had not given up on the concept of energy conservation through the forced reduction of infiltration rates in new homes.

While efforts to promulgate BEPS were under way, the DOE was concurrently developing a Residential Conservation Service Program (RCS) to encourage the installation of energy conservation measures in existing homes. Called for under Part 1 of Title II of the National Energy Conservation Act (Pub. L. No. 95-619, 92 Stat. 3206, et seq), the program requires states to develop plans under which utility companies and/or heating fuel suppliers will offer energy audits to homeowners, offer assistance in arranging for installation of recommended conservation measures, and assist in financing costs. The proposed rules were first published in the Federal Register of March 19, 1979. After conducting eight public hearings and receiving numerous written comments, DOE published the final rules in the Federal Register [9] on November 7, 1979. They were accompanied by a final environmental impact statement [10].

The U.S. Environmental Protection Agency (EPA) and others commented on the subject of indoor air quality impacts in response to the publication of the proposed rules, and their comments were summarized in the preamble to the final rules. EPA listed several pollutants which could be generated within residential buildings with special reference to carbon monoxide and nitrogen dioxide generated from poorly ventilated space heaters, gas stoves, and clothes dryers. In addition, it commented upon potential problems with formaldehyde, radon, and radon daughters. A number of recommendations were made to ensure that energy audit customers are provided specific information on the need for adequate ventilation, to ensure that adequate safeguards are taken to mitigate the hazards of radon, to ensure that stringent standards are set on the free formaldehyde content of urea-formaldehyde foam insulation, and so forth. DOE agreed in a number of areas to amend the final rules or to study the issues further. In doing so, it noted that it heads an inter-agency task force on indoor air quality, that it recognizes the seriousness of the potential problems from indoor air pollutants, and that it is continuing a substantial research program on these issues.

The Lawrence Berkeley Laboratory (LBL) commented that DOE's draft environmental impact statement seriously understated the potential impact of measures which reduce air infiltration rates on indoor air quality, and, hence, on the health of occupants. LBL expressed particular concern about radon concentrations and about the formaldehyde issue. In response, DOE again stated its intention to propose an amendment to the final rule to address ventilation, and agreed to revise its environmental impact statement.

After further consideration of indoor air quality issues, and months of negotiations between DOE and EPA, the EPA recently published (July 1980) its first major position paper [11] on indoor air pollution and outlined various suggestions to DOE concerning the RCS Program. The DOE agreed to incorporate these suggestions into the final rule.

EPA's position paper reviewed the sources of indoor air pollutants and their associated health effects, described control measures that may help to reduce exposure to radon decay products and other indoor air pollutants, and discussed the benefits and risks of conservation measures that decrease building air exchange. It then proposed specific wording for inclusion into DOE's rules that requires energy auditors to inform customers about potential indoor air pollution problems, with special reference to radon. In addition, auditors are instructed to recommend measures or practices that would significantly reduce the infiltration rate <u>only</u> when:

(a) The anticipated final infiltration rate will equal or exceed that of the average U.S. residence (estimated to be one air exchange per hour), or;

(b) Measures which have been proven effective (Section 4) are concurrently recommended which will at least maintain indoor air quality relative to the significant sources of pollutants identified under Section (1)(i).

Control measures listed in Section 4 included: (a) elimination of the source; (b) installation of an air-to-air heat exchanger coupled with a forced ventilation system providing no less than one air exchange per hour; (c) installation of an electrostatic air filtration device or other air filtration system; (d) installation of an exhaust ventilation system near the source of pollutant; or, (e) greater use of natural ventilation (e.g., open windows) or mechanical ventilation (e.g., window fans) at appropriate times. Sources of pollutants listed under Section (1)(i) were: (a) unvented gas or oil heating equipment, and clothes dryers; (b) unvented cooking appliances; (c) urea-formaldehyde foam insulation; (d) particle-board and plywood containing aldehyde resin glues; (e) asbestos insulation and building materials; (f) motor vehicles operated in attached garages; (g) tobacco smoke; (h) aerosol sprays; and (i) radon from soil, water or building materials.

In discussing EPA's proposal, the DOE noted that "health risks from radon appear to be the most significant of all indoor pollutants" and stated the intention to make a special effort to study this problem.

Additionally, it asked the public for comments on EPA's proposal [11]. Although the policy of Federal agencies regarding energy conservation and indoor air quality has not been fully developed, it appears that:

- The Federal government has fully recognized the potential adverse impact of reducing infiltration rates in homes for the purpose of energy conservation.
- New regulations will not encourage infiltration rate reductions unless there is excessive infiltration or control measures concurrently reduce pollutant levels to pre-existing or acceptable levels.
- Further studies will take place with the purpose of better defining the scope and magnitude of indoor air quality problems, to identify the strength of pollution sources in houses, and to prescribe a plan to reduce infiltration which preserves indoor air quality and takes into account factors specific to individual houses.

5.4 PERTINENT INDUSTRY ACTIVITIES

The American Society of Heating, Refrigeration, and Air-Conditioning Engineers (ASHRAE) has had a considerable impact on building codes in recent years. In 1975, it developed its Standard 90-75 called "Energy Conservation in New Building Design" as a consensus standard [6] which specifies the maximum infiltration rates allowable through windows, sliding glass doors, and entrance swinging doors for residential use, mostly by referencing existing ANSI standards. Since the designers of home heating and cooling systems generally rely on natural air infiltration to provide fresh air infiltration, it is evident that Standard 90-75 mostly impacts indoor air quality in homes through its call for comprehensive sealing of leakage paths, and that the extent to which builders will go in finding and sealing all paths is somewhat up to their own discretion. If the general wording of the standard was interpreted literally, all homes would be built with extremely low infiltration rates.

The fact that ASHRAE did not fully consider the impact of its standard on indoor air quality in 1975 is evidenced by the reference to Standard 62-73 that requires the use of the minimum ventilation rates listed therein when HVAC systems are installed. James Repace from EPA's Office of Policy Analysis recently noted [13] that the minimum rates were based on human metabolic needs for oxygen, while the higher "recommended" rates given in the standard were based on the necessity to control odor (set on the basis of experiments done in the 1930's). He went on to note that the specification of minimum rates did not recognize that there were non-industrial sources of indoor air pollution, and that their use has led to uninhabitable buildings being constructed. Dr. James Woods, Chairman of ASHRAE's Standards Project Committee, essentially agreed with Repace's statement when he wrote [5] that the requirement of Standard 90-75 "is the cause of serious concern in new buildings."

Although Standard 62-73 and therefore Standard 90-75 still have some unresolved problems in the indoor air quality area, ASHRAE is officially of the opinion that its Standard 90-75 should be considered the equivalent to DOE's Building Energy Performance Standards (BEPS), and has quite strongly implied that it considers its standard the better package of the two. At the DOE hearing on March 24, 1980, ASHRAE President Hugh P. McMillan, Jr., outlined [14] ASHRAE's seven major concerns with BEPS as they now stand. These generally involved cost of implementation, requirement of a computerized energy analysis that "effectively discriminates against...small businesses," incomplete research, incomplete documentation of research, small sample sizes, excessive complexity, and lack of an implementation plan. McMillan then went on to note that codes based in whole or in part upon Standard 90-75 are now in effect in 44 states, and concluded [14]:

- "That there is a significant advantage for the nation in maintaining and strengthening these standards and codes (i.e., Standard 90-75) rather than replacing them with the whole building performance approach as proposed (i.e., BEPS);

- "That it is in the interest of our nation to implement a BEPS program with equivalent subsystem performance standards (i.e., Standard 90-75) in parallel with the whole building procedures...; and

- "That a realistic time schedule spanning a three-to-five-year period be provided for the completion of the development and implementation process."

Other industry groups have also criticized BEPS for various reasons [15]. Merrill Butler, President of the National Association of Home Builders (NAHB) stated the standards would be "unworkable and impractical to administer locally, "and called the Standard Evaluation Technique (SET) (a part of BEPS)" not only beyond the capability of builders and building officials, but also most of the design professionals in this country."

In a more pertinent vein, Butler stated [15] that the SET suffers from technical difficulties, the most offensive being that the reduction of air infiltration, a notable energy loser, will be discouraged, since the SET assigns an arbitrary minimum rate of 0.6 changes per hour. He added that "the reduction of air infiltration is a very large factor in reducing energy consumption as compared with increased amounts of insulation and multi-glazed windows and therefore a much more cost-effective means of providing added thermal protection."

This latter statement by Butler, if he was quoted correctly, typifies some of the confusion that has recently taken place over the subject of air infiltration rates and their relationship to indoor air quality.

Since DOE's proposed regulations did not set a minimum on infiltration rates at the time of Butler's statement, it is apparent that the regulations were being misunderstood. This is not very surprising, since in the course of a few years, the Government's position vis-a-vis infiltration rates is on the verge of a complete about-face on the matter.

In summary, the situation in the industrial sector at present appears to be that:

- The current ASHRAE standards that have been codified and adopted by the States on a widespread basis are deficient in their treatment of potential indoor air quality problems.

- Efforts to resolve problem areas are well underway. The basic approach being taken may or may not be found adequate in the long-run.

- ASHRAE is strongly lobbying to get its Standard 90-75 declared the equivalent to DOE's BEPS standards.

- There are elements of the building industry that are ignoring potential air quality problems resulting from reduced infiltration and arguing that reduction of air infiltration be allowed to meet Federal energy conservation objectives.

5.5 PAST AND CURRENT TRENDS

Over the past decade or so, considerable publicity has been given to the need to conserve energy and to the benefits available to consumers through simple measures to reduce the effect of air infiltration and other energy loss mechanisms in homes. The measures most often discussed have included weatherstripping, caulking insulation, and installation of storm windows and doors. There has been a profileration of articles on the topic in the popular press and literature, and the Federal government has provided homeowners with incentives in the form of tax credits to ease the cost burden. In addition, as discussed above, there has been action in the regulatory area to mandate energy-efficient construction of new buildings. It is the intent of this section to assess the impact these activities have had on the infiltration rates typically found in North American homes.

5.5.1 Existing Homes

The basic question in regard to the impact of retrofitting existing homes to conserve energy cannot be fully answered quantitatively due to a paucity of hard data on the subject. Thus, it is necessary to derive an answer somewhat qualitatively.

A study [2] published by the Office of Technology Assessment (OTA) in 1979 provides information about consumers that is relevant. In short the OTA found that:

- Consumers are most willing to conserve energy where fuel costs are high and climatic conditions extreme.
- While lower-income households have the greatest need to conserve energy, they also suffer from a lack of opportunities to do so. There is very little fat in the poor family's energy budget.
- The smaller impact of rising energy costs on upper-income households has not generally provided sufficient motivation to conserve.
- The middle-income group offers the greatest potential for energy conservation, since this group has both an economic margin for conservation and economic incentive to do so.
- An estimated one-half of all property improvements are done on a do-it-yourself basis. The most common types of retrofit energy saving improvements are installation of insulation, storm windows, caulking and weather-stripping around doors and windows, and furnace replacement or improvements in furnace efficiency.
- Government efforts to help consumers determine savings potential and to provide practical "how to" information have either been too complex or not been made widely available.

The OTA's findings generally lead to the observations that there are large segments of society that are not and have not been in a financial position to implement comprehensive energy conservation measures, that have not in the past had a significant economic incentive to do so, or that have not been provided readily available and understandable information on how to proceed. In addition, they lead to the observation that efforts to reduce air infiltration have centered upon caulking and weatherstripping around windows and doors, installation of storm windows and doors, and to a limited extent, installation of insulation.

In the preceding chapter addressing air infiltration, it was generally demonstrated that attention to doors and windows has a lesser impact upon infiltration rates than is generally envisioned, and that additional insulation in attics and/or crawl space ceilings can sometimes cause an increase in infiltration rates. It was also shown that the average homeowner, and even the average contractor, would have considerable difficulty in identifying all the major leakage paths into a particular home and in finding ways to reduce their impact. This contention was not explicitly proven. Rather, it evolved from the observation that it usually required skilled researchers using custom-fabricated, specialized equipment to make a major impact on infiltration rates. Thus, a preliminary conclusion is that the generally applied methods to reduce infiltration rates in existing homes in the past have had limited success, and it remains to assess their overall impact on infiltration rates.

A great deal of the literature on infiltration cites an old rule-of-thumb that leakage rates vary from 0.5 to 1.5 ACPH and average about 1.0 ACPH in homes. The overall range is cited in the ASHRAE Handbook of Fundamentals [16] with reference to six papers written between 1957 and 1964. The Handbook specifies that the range represents winter conditions, but that particular qualification is often lacking in other sources. It is not completely clear where the average of 1.0 ACPH originated, but it would not be unreasonable to envision that it is simply the midpoint of the specified range. Not surprisingly, the EPA [11] uses the 1.0 ACPH rate in its proposed text for inclusion into DOE's rulemaking for the Residential Conservation Service Program.

A close inspection of all the ranges of infiltration rates measured in homes over the last two or so decades (see previous chapter) provides somewhat different results when the data of Grot and Associates [17] are deleted for low-income housing and Caffey's results [18] are set aside due to possible problems with their accuracy. Indeed, for the 40 or so homes considered, the overall range in round numbers is 0.1 to 1.8 ACPH when two unusual structures (a very leaky mobile home and a specially constructed experimental residence) are dropped from consideration. The arithmetic average for these homes is on the order of 0.6 ACPH (<u>not</u> on a time-weighted basis). Grot [17] found that the average rate for the 266 low-income homes was 0.86 ACPH. If the data are integrated, the average then becomes about 0.83 ACPH. If indeed the 1.0 ACPH average cited was correct at one time in the past, then it <u>appears</u> that there is <u>some</u> evidence that infiltration rates have dropped by roughly 15 to 25 percent on the average over the last two or three decades due to progressively better construction techniques and materials and the retrofit of older homes.

The section on "Leakage Paths" in the previous chapter essentially demonstrated that exterior windows and doors contribute no more than 25 percent or so of the total air leakage into a home, and as little as 5 percent under certain circumstances. The difference between the extremes is probably indicative of the realizable reduction in infiltration rates due to weatherstripping and caulking, and installation of storm windows and doors, and is consistent with previous findings.

It is possible to use these bits and pieces of data to develop tentative conclusions about the past and current trends in air infiltration rates due to retrofit of existing homes. The conclusions admittedly cannot be well supported, but can be considered reasonable and consistent with apparent facts. They include the findings that:

1. The current generation of residences appear to have an average annual infiltration rate between 0.6 and 0.86 ACPH, depending on the mix between well-built and well maintained homes and what can be termed "low-income housing." The true average is likely to be in the upper end of the range.

2. Given the assumption that homes built more than two decades ago had an average infiltration rate of 1.0 ACPH, it appears that the average rate has dropped by 15 to 20 percent or so over time.

3. Retrofitting of older homes with common methods can probably reduce infiltration rates by no more than 20 to 25 percent.

4. The average infiltration rate in homes currently existing will slowly decrease as energy costs rise and more and more families find that energy conservation is an economic necessity.

5.5.2 New Homes

It is rather evident that some builders have been taking extraordinary measures recently to reduce infiltration rates in new homes and thereby conserve energy. Grimsrud and Associates [19] measured an overall range of 0.08 to 0.13 ACPH for an especially energy-efficient home built in Minnesota in 1978. This range would not be unusual for many homes under conditions of negligible wind and indoor-outdoor temperature difference. In this particular case, however, the wind velocity ranged from 3 to 5 m/s (6.7 to 11.2 mph) and the indoor-outdoor temperature difference ranged from 77 to 79°F during measurements. A "normal" home under these conditions would experience substantially higher rates.

In a similar home built in 1977, Grimsrud and coworkers [19] measured a range of 0.10 to 0.12 ACPH when the wind velocity varied from 4 to 8 m/s (9 to 18 mph) and the temperature difference remained constant at about 72°F. Again, these are remarkably low rates for fairly severe weather conditions. One must wonder whether the infiltration rates would even be measurable at somewhat lower wind speeds and temperature differences.

Although these particular homes are likely to be rare examples, the question that arises is: to what extent are homes today being built tighter than their counterparts constructed years ago? Unfortunately, due to a lack of hard data, it is again necessary to resort to somewhat qualitative reasoning to develop a plausible answer. The task is again facilitated by reference to the 1979 study [2] by the Office of Technology Assessment.

In discussing the role of the builder in energy conservation, the OTA noted that builders are adaptable and willing to change the characteristics of the housing they build, but only as a result of proven market demand. They are reluctant to pioneer unproven changes that may adversely affect the marketability of housing and meet consumer resistance. In addition, speculative builders must be concerned about the cost of adding standard features and will carefully weigh costs against the advantages of these features in helping to sell housing. Citing various surveys, the OTA goes on to note that builders have mostly been utilizing simple conventional equipment and materials over the last two years to reduce energy consumption. The most common features, with their associated level of implementation, have included:

Features	Percentage of New Homes
Increased attic insulation	83
Double/triple glazed windows	67
Improved weatherstripping/caulking	50
Roof overhangs	50
Heat pumps	39
Attic fans	29

At least four of these features can have an effect on home infiltration rates. Increased attic insulation may directly or indirectly lead to a reduction in the leakage paths above living spaces and thereby lead to a possible reduction in infiltration rates under some circumstances. Conversely, however, it is notable that Burch and Hunt [20] measured a small but systematic increase in infiltration when the attic and crawl space ceiling of one house were insulated, causing a significant increase in the temperature difference between the living space and the spaces immediately above and below.

Double or triple glazed windows themselves are likely to have only a marginal effect on infiltration rates due to the increased number of glass layers. It is not unreasonable to expect, however, that the overall air leakage rate through such window assemblies will be lower than usual due to the nature and generally better quality of their construction.

Improved weatherstripping of doors and windows will help to reduce rates to a limited extent. Caulking major leakage paths during construction is likely to have a greater impact than would caulking of windows and doors as a retrofit measure for existing homes.

It is not at all clear what the effect of attic fans would be on infiltration rates, since reference to the subject could not be found in the literature. It is evident from basic principles, however, that the potential for impact exists through a number of mechanisms involving temperature and pressure differences across building interfaces.

Data discussed above indicated that typical modern homes, i.e., those considered well-built and well-maintained, probably have an average infiltration rate on the order of 0.6 ACPH. In addition, reference was made to building standards that require infiltration rates of 0.7 ACPH or less for single-family residences, and lower rates for other types of dwellings. Thus, it appears that:

1. Many new homes have an average infiltration rate below 0.7 ACPH. The average is likely to be 0.6 ACPH or lower.

2. A small number of homes are being built with very low infiltration rates on the order of one or two tenths of an air change per hour.

3. New homes have lower infiltration rates than their counterparts built in decades past due to better construction techniques and materials.

5.6 FUTURE TRENDS

Given the current knowledge in this subject area, and the general cautious attitude of the Federal Government, proponents of energy conservation require a clear and definitive finding that indoor air quality is not a problem at present and that widespread reductions in air infiltration rates in new and existing housing will not lead to problems in the future. On the other hand, if it is definitively found that American homes are currently on or near the borderline between acceptable and non-acceptable internal air quality, or in any set of circumstances leading to a non-definitive finding about acceptability, efforts to reduce air infiltration will probably be discouraged.

Overall, one would expect that the current downward trend in air infiltration rates will continue into the near future due to its "momentum." Results of current and future studies examining the relationship between health effects and reduced air infiltration may modify this trend. In the meantime, the public will be informed about indoor air quality through the news media and popular literature. Home builders may be discouraged from building tighter homes by increased awareness of potential problems and, possibly, by regulations that set forth a minimum allowable infiltration or total ventilation rate in new homes. Furthermore, increasing pressure may be brought to bear on the providers of building materials and certain appliances to reduce pollutant emission levels from their products and/or to develop effective controls.

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6. INDOOR-OUTDOOR POLLUTANT RELATIONSHIPS

6.1 INTRODUCTION

The concentrations of airborne contaminants at a particular location in a home are a complex function of indoor pollution source strengths, times these sources are activated, air infiltration or ventilation rates, quality of infiltrating air as a function of time, and the rates (if any) that contaminants decay. Each of these variables is itself affected by numerous other factors, as has been demonstrated thus far for air infiltration rates into homes.

It is the intent of this chapter to provide an overview of the interrelationships between the most significant variables with the objective of:

- Demonstrating the relative importance of individual factors;
- Providing a proper perspective to the overall problem area; and
- Defining the questions that must be answered in any comprehensive assessment of the impact of indoor air pollution on public health.

The entire subject area is one that is very complex. Thus, this chapter looks at one aspect of the problem at a time in simple qualitative terms before considering their integrated impact. While doing so, it highlights various observations that are worthy of future consideration in the development of a plan of action to cope with the indoor air quality problem.

6.2 THEORETICAL RELATIONSHIPS

An analytical model of indoor-outdoor pollutant relationships can provide a useful tool for evaluating the impact of various parameters on indoor air quality. Various researchers have attempted to develop such models and to validate them with available data. Examples include the efforts of Milly [1], Calder [2], Turk [3], Hunt et al [4], Shair and Associates [5, 6], Moschandreas et al [7, 8], Silberstein [9], Esmen [10], Sutton et al [11] and numerous others.

The majority of models are derived from a fundamental mass balance that accounts for the various sources and sinks of pollutants in the home or other structure of interest. Typically, the basic relationship utilized is of the form:

$$V \frac{dC_{in}}{dt} = V\,v\,C_{out} + S - V\,v\,C_{in} - VDC_{in},$$

where

C_{in} = indoor pollutant concentration, mass/volume

C_{out} = outdoor pollutant concentration, mass/volume

V = building volume, volume

v = air exchange rate, air changes per hour (ACPH)

S = indoor pollutant emission rate, mass/time

D = decay factor, $time^{-1}$

The term on the left-hand side of the equation represents the rate at which a particular pollutant will accumulate in a given space in units of mass/time. The first term on the right side denotes the rate at which the pollutant enters the building with outdoor air, while the second term is the rate at which the pollutant is internally generated. The third term is the rate at which the pollutant leaves the building with indoor air through exfiltration or other mechanisms. The fourth term is the rate of pollutant decay (see below) due to interactions with building furnishings.

In the process of obtaining a closed-form solution to this differential equation, researchers have incorporated various modifications designed to permit variation in model input parameter values with time and/or to address other phenomena. These have typically involved changes in infiltration rate, outdoor pollutant concentration, indoor pollutant generation rate and decay rate with time, as well as consideration of deviations from perfect mixing of the various air streams.

In a major effort on indoor air quality for the EPA, GEOMET, Inc. [7] developed an estimation procedure using this basic approach that was well-supported by the data gathered in its study, yet fairly simple and straight forward in application. Following the lead of Shair and Heitner [5], GEOMET allowed the outdoor pollutant concentration over fairly short time intervals to be represented by the straight-line relationship:

$$C_{out} = m_{out}\,t + b_{out}$$

where m_{out} is the slope, t is the time, and b_{out} is the y-intercept. It then obtained a closed-form solution to the differential mass balance equation and developed a procedure that permits changes in air exchange, internal emission, and decay rates with time. This was accomplished by utilizing the equation over short time steps during which the various rates could be considered constant. Thus, GEOMET's ultimate equation for a given time interval balance became:

$$C_i = [C_{i-1} - m_i (\frac{v_i}{D_i + v_i}) t_{i-1} - (\frac{1}{D_i + v_i}) (v_i b_i + \frac{S_i}{V} - \frac{m_i v_i}{D_i + v_i})]$$

$$e^{-(v_i + D_i)(t_i - t_{i-1})} + (\frac{1}{D_i + v_i})(v_i b_i + \frac{S_i}{V} - \frac{m_i v_i}{D_i + v_i}) + m_i (\frac{v_i}{D_i + v_i}) t_i$$

where

C_i = the indoor pollutant concentration level at time t_i, $i = 1, \ldots, n$

$C_{out}(t)$ = the outdoor pollutant concentration level at time t

m_i = $[C_{out}(t_i) - C_{out}(t_{i-1})]/(t_i - t_{i-1})$, $i = 1, \ldots, n$

b_i = $C_{out}(t_i) - m_i t_i$, $i = 1, \ldots, n$

S_i = internal source rate over the interval $[t_{i-1}, t_i]$, $i = 1, \ldots, n$

v_i = air exchange rate over the interval $[t_{i-1}, t_i]$, $i = 1, \ldots, n$

V = volume of the building

D_i = decay factor over the interval $[t_{i-1}, t_i]$, $i = 1, \ldots, n$.

About the only major assumption that remains in the model formulation involves the assumption of instantaneous and perfect mixing between all air streams and pollutant volumes in the internal space being considered. Thus, the model estimates the average contaminant concentration in the space and cannot discern point to point variations due to localized pollutant sources or imperfect mixing of air volumes. This may eventually prove to be a shortcoming when and if the model is applied to the task of estimating time-weighted average exposures for home inhabitants based on the amount of time spent in each of several rooms with differing pollutant levels. At present, however, the model is more than adequate for use in identifying important variables and studying their basic interrelationships. Subsequent sections of this chapter describe and discuss the various phenomena that impact upon indoor air quality. To illustrate relationships between factors, the chapter occasionally draws upon the results of analyses conducted by GEOMET using the model. Frequently, variations of the mass balance equations are independently utilized to study or illustrate relationships not addressed by GEOMET.

6.3 IMPACT OF INDOOR POLLUTION SOURCES

6.3.1 Nature of Indoor Sources

Indoor sources of air pollutants can generally be disaggregated into those that are more or less continuous in nature and those that are intermittent. Among the former category can be included:

- Radon decay products from soil under buildings, from building materials such as concrete and brick, and from open drains or leaking faucets containing tap water taken from wells or underground springs;
- Water vapor from open drains, humidifiers, plants, rodents, pets, refrigerators and freezers, leaking faucets, exposed foods, etc.;
- Formaldehyde or other aldehydes from urea-formaldehyde foam insulation, from particle board and plywood used in home construction or furniture, and from other items made with aldehyde resins;
- Disease microorganisms from pets, rodents, insects, and plants;
- Carbon dioxide, nitrogen oxides, carbon monoxide, and water vapor from unvented gas pilot lights; and
- Asbestos from building materials and possibly household appliance.

Sources of pollutants that are generally intermittent in nature and that are dependent upon the presence of humans or a control mechanism to turn them on or off include:

- Radon from tap water used for drinking, cooking, bathing, washing dishes, cleaning house, etc.;

- Disease microorganisms, carbon dioxide, water vapor, and odoriferous substances from humans, pets, or rodents that occupy the home on an intermittent basis;

- Carbon dioxide, nitrogen oxides, carbon monoxide, and water vapor from operating unvented gas stoves, unvented gas space heaters, or oil or gas furnaces that are imperfectly vented;

- Numerous contaminants from the smoking of cigarettes, cigars, and pipes;

- Increased dust levels due to vacuum cleaning or movement on the part of occupants;

- Numerous contaminants from use of aerosol sprays and other consumer products containing volatile chemicals;

- Various contaminants due to cooking of food;

- Asbestos from use of certain appliances;

- Ozone from household devices; and

- Carbon monoxide, hydrocarbons, nitrogen oxides and other substances from motor vehicles moving in and out of attached garages.

The indoor pollutant sources that are continuous in nature will often generate contaminants into the indoor environment at a more or less constant rate over time periods of moderate duration, and will thus contribute to what can be termed "baseline" levels of contaminants in the air. Intermittent sources of pollution make up the difference between baseline levels and levels that may actually be measured in a home. Depending upon the habits of occupants and environmental conditions, some of these sources may be activated in somewhat of a predictable fashion on a daily basis, an example being the cooking of dinner at a certain time each day. Yet others may take place somewhat randomly in time.

6.3.2 Source Strengths and Decay Factors

The rate at which a contaminant is released into the environment from a particular source can vary from home to home as well as from one time to another in a particular home. For example, it is possible to visualize two homes with different amounts of materials that generate formaldehyde. All other things being the same, the home with the greater amount of such materials is likely to experience the higher levels of formaldehyde. Similarly, it can be envisioned that the duration of unvented gas stove use and other intermittent activities in any home can vary from day to day or season to season, thus affecting the total amount and nature of pollutants being released to the internal environment.

The airborne concentrations of certain contaminants such as ozone, nitrogen dioxide, and sulfur dioxide decay at various rates due to absorption or adsorption on indoor surfaces or reaction with available materials. The rates at which these contaminants may disappear from the air will vary as a function of the exposed room surface area, the nature of surfaces, internal temperature, humidity, and so forth. Likewise, particulate matter in air may settle upon exposed surfaces in a fashion similar to common atmospheric dust. Table 6-1 summarizes the decay factors that were utilized in the GEOMET study [7] and that are used in this chapter for example purposes.

Figure 6-1 is the result of applying the mass balance equations to a number of hypothetical scenarios involving the generation of nitrogen dioxide from gas stove operation. All curves are based on the assumptions that the air exchange rate is a constant 1.0 per hour, that the internal volume of the space is 1000 cubic feet, and that the outdoor air is free of the contaminant.

Curve A represents the internal average concentration expected due to continuous operation of the pilot lights on the stove using a nitrogen dioxide emission rate of 1.9 mg/hr [12] and assuming that nitrogen dioxide does not decay, although in actuality it does. Curve B is for the same conditions as A, but uses a nitrogen dioxide emission rate twice that of A, thus showing the effect of increased emission rates. Curve C uses the emission rate of A, but assumes a nitrogen dioxide decay factor of 1.39 per hour from Table 6-1, thus illustrating the reduction in concentration due to decay effects.

Curve D on the figure looks at the concentration levels expected if the pollutant does not decay and if a single burner with an emission rate of 277.0 mg/hr [12] is operated for one hour during the given time span. Curve E is similar to D but realistically permits pollutant decay. In both of these cases, the pilot lights continue to operate.

Inspection of these curves demonstrates the general findings that (1) concentrations are generally proportional to emission rates for pollutants generated in the indoor environment; (2) pollutants that decay will be at lower levels than similar pollutants that do not decay; and (3) pollutants that do not decay are more persistent than those that do and will attain greater levels for a given intermittent source activation.

It should be noted that the emission rate utilized in this example may not be representative. For example, data from the laboratories of the American Gas Association suggest that burner emissions rates for nitrogen dioxide are closer to 100 mg/hour. Substitution of the lower emission rate into this model would result in significantly lower peak levels.

TABLE 6-1

DECAY FACTORS USED IN GEOMET STUDY [7]

Pollutant	Decay Factor* (per hour)
CO	0.00
SO_2	1.04
NO	0.00
NO_2	1.39
O_3	34.66
CH_4	0.00
THC	0.00
CO_2	0.00
$THC-CH_4$	0.00

*The decay factor is defined as the natural log of 2.0 divided by the half-life of the pollutant considered in units of hours.

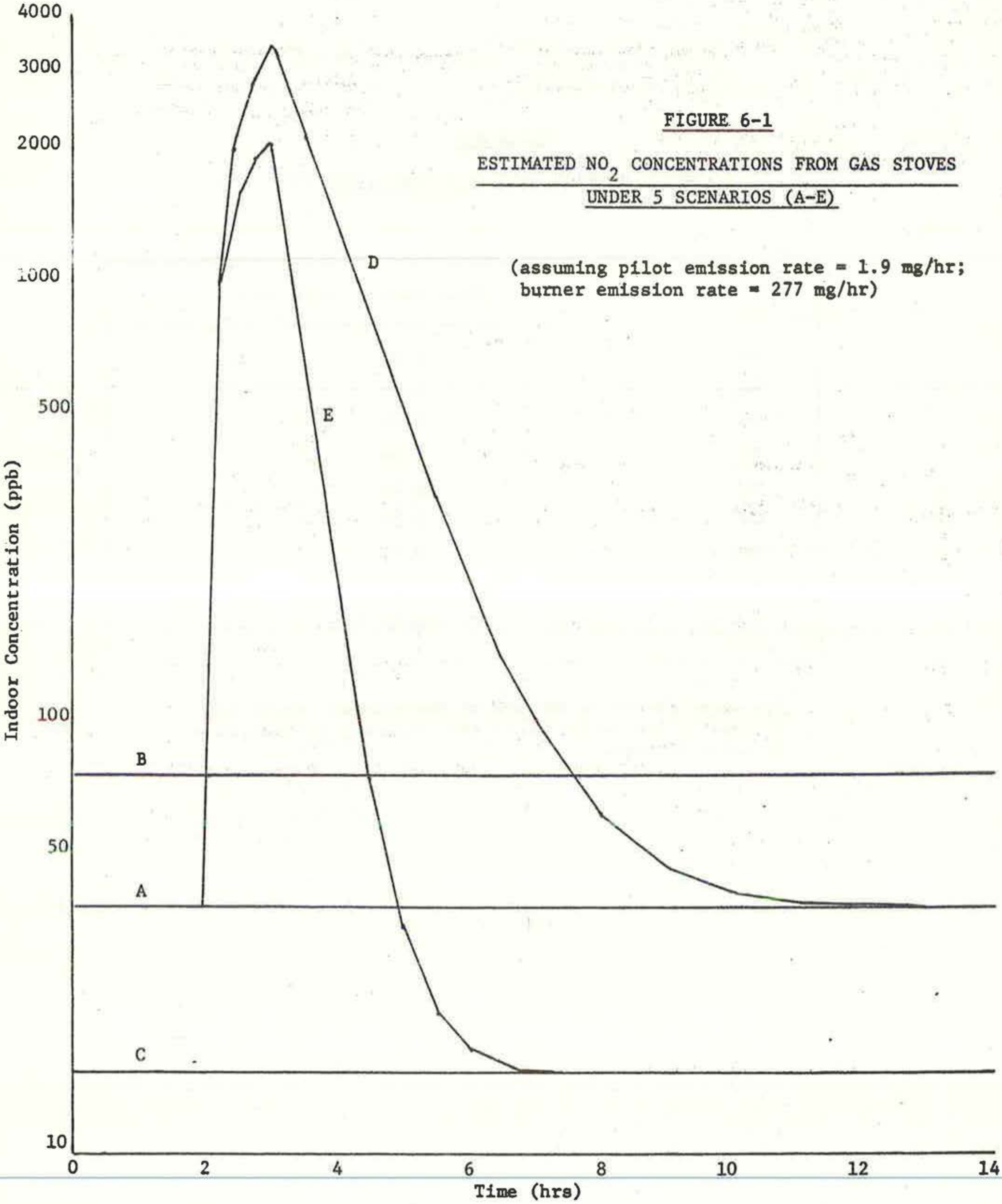

FIGURE 6-1

ESTIMATED NO_2 CONCENTRATIONS FROM GAS STOVES UNDER 5 SCENARIOS (A-E)

Source: Arthur D. Little, Inc.

6.3.3 Spatial Distribution of Sources

Some of the sources of indoor air pollution listed above are well-distributed throughout a home while others are usually localized. For example, urea-formaldehyde foam insulation, if present, is likely to be found in all exterior walls of the building envelope. A gas stove, however, will be found in the kitchen with few exceptions. It follows that formaldehyde has the potential to be more evenly distributed throughout the home than contaminants generated by stove operation.

Figure 6-2 presents data obtained [7] for aldehydes in an experimental home in Chicago. It is quite clearly shown that (1) indoor concentrations greatly exceed outdoor levels; (2) indoor levels fluctuate over a wide range due to various factors; and (3) concentrations measured in a kitchen, bedroom, and living room are quite similar. In contrast, Figure 6-3 presents the results of an experiment in a Washington experimental home where tracer gas was continuously released in a kitchen and concentrations were measured in a nearby bedroom and living room. In this case, the bedroom and living room levels increased over the course of about 90 minutes and reached what appears to be a steady-state level well below the kitchen level. Clearly, an individual in the kitchen during this experiment would have a different exposure to the tracer gas than individuals in other locations. Figure 6-4 shows the differences between rooms for a high-rise apartment. It is noteworthy that total suspended particulate (TSP) levels in the kitchen typically exceed outdoor levels as well as levels in a bedroom and living room.

6.3.4 Impact of Ventilation Rates

As outdoor air enters and leaves a home through the processes of infiltration, exfiltration, or natural ventilation, it will have an impact on the indoor pollutant concentrations experienced. Higher rates of ventilation generally lead to lower indoor pollutant concentrations, and lower rates generally lead to higher concentrations. This finding is fundamental to the principle of dilution ventilation regardless of whether air movement is induced by natural forces or mechanical means.

Figure 6-5 presents the results of an analysis using the mass balance equations to study the effect of air change rates on indoor carbon monoxide (CO) concentrations due to unvented gas oven operation. The analysis assumes that the oven generates 3564 mg of CO per hour [12], that it is operated for two hours starting at time zero, that the air entering the home does not contain CO, that there was no CO present in the indoor air at time zero, that the home has a volume of 15,000 cubic feet, and that the CO generated is well-mixed with all the air in the home. The results clearly demonstrate that indoor concentrations and exposures due to indoor sources are highly sensitive to air exchange rates, with high rates resulting in lower levels and exposures and low rates resulting in higher levels and exposures.

CHICAGO EXPERIMENTAL RESIDENCE

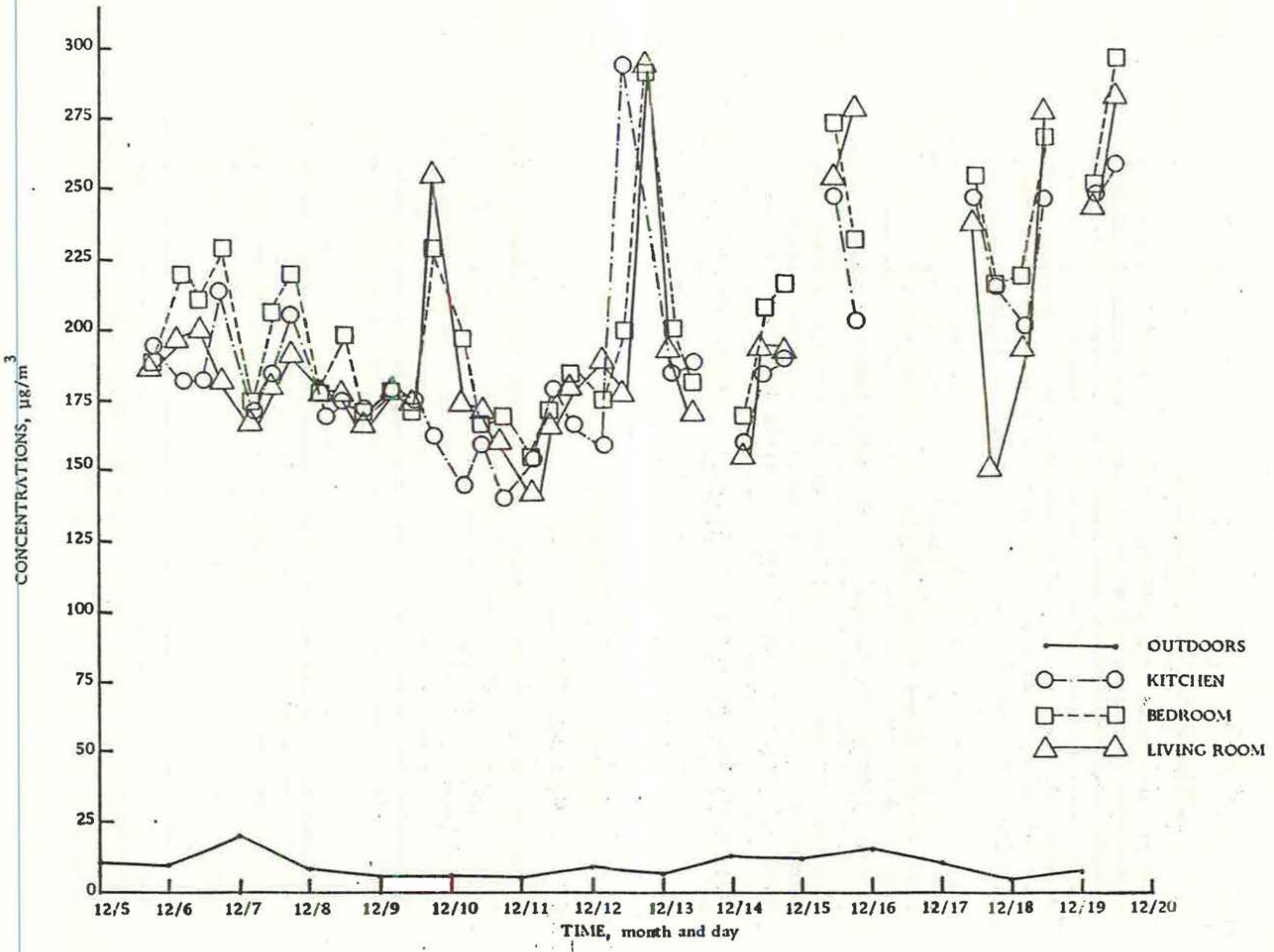

Figure 6-2 : Aldehyde concentrations in a Chicago residence [7]

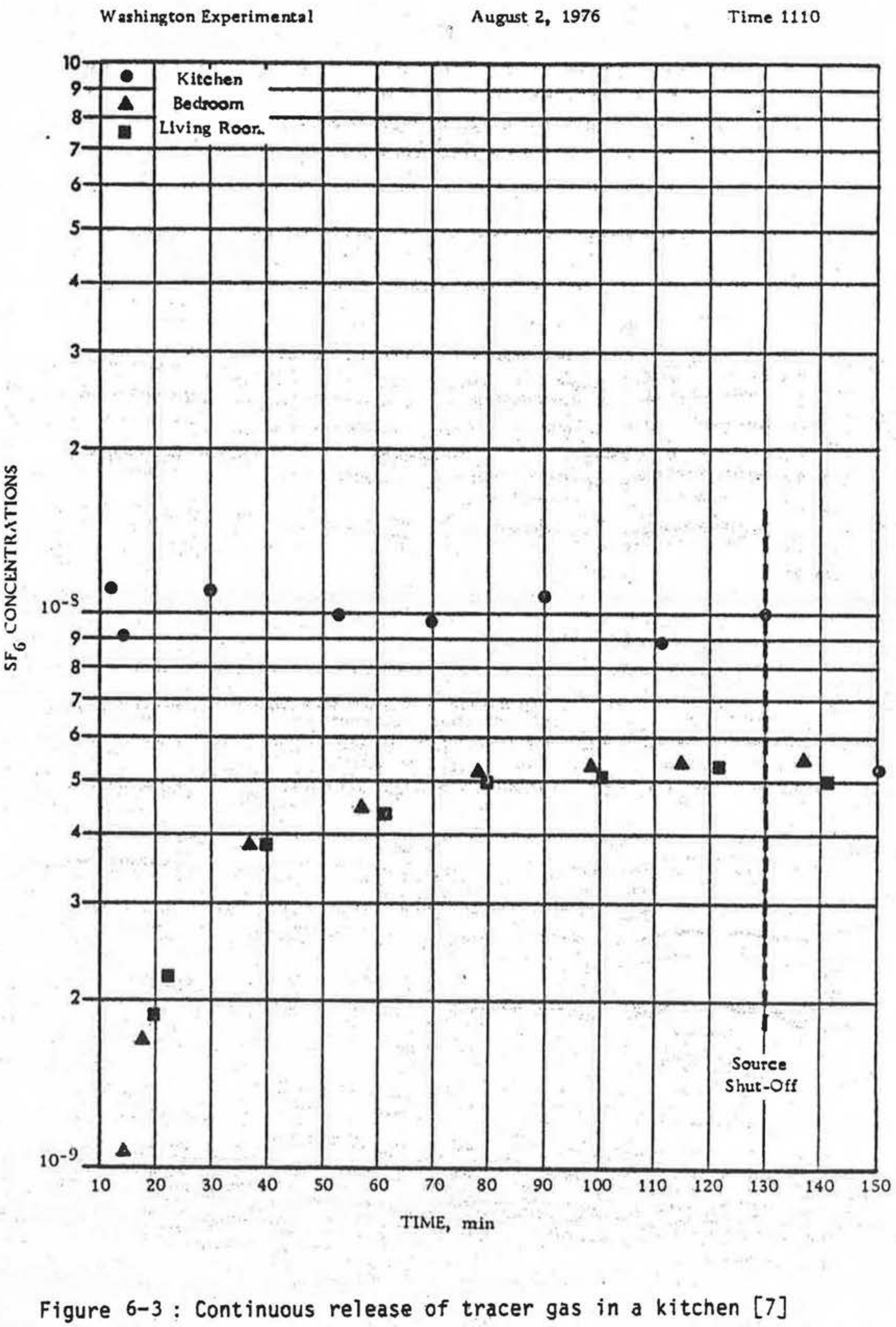

Figure 6-3 : Continuous release of tracer gas in a kitchen [7]

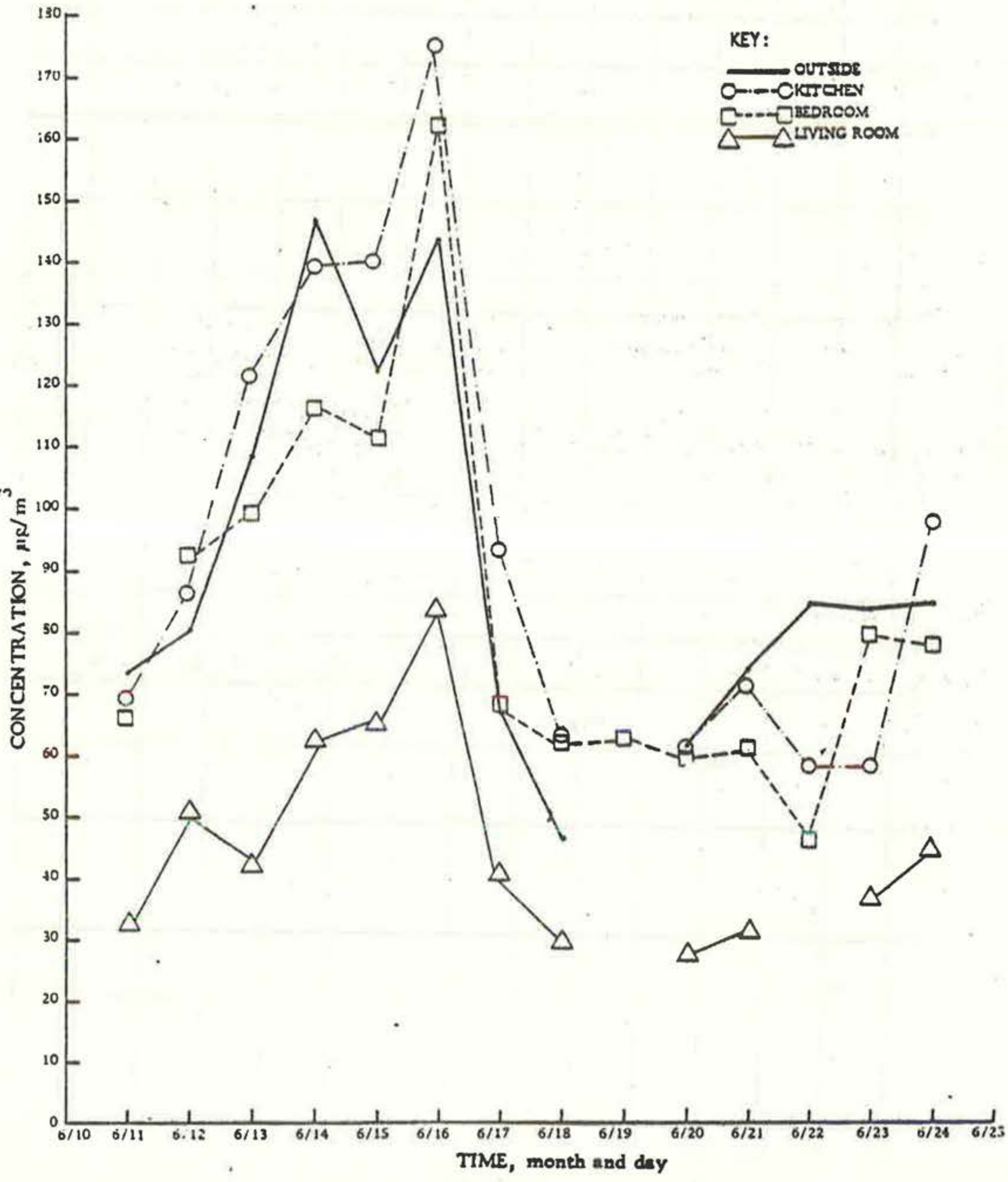

Figure 6-4 : Indoor TSP levels in a Pittsburgh high-rise apartment [7]

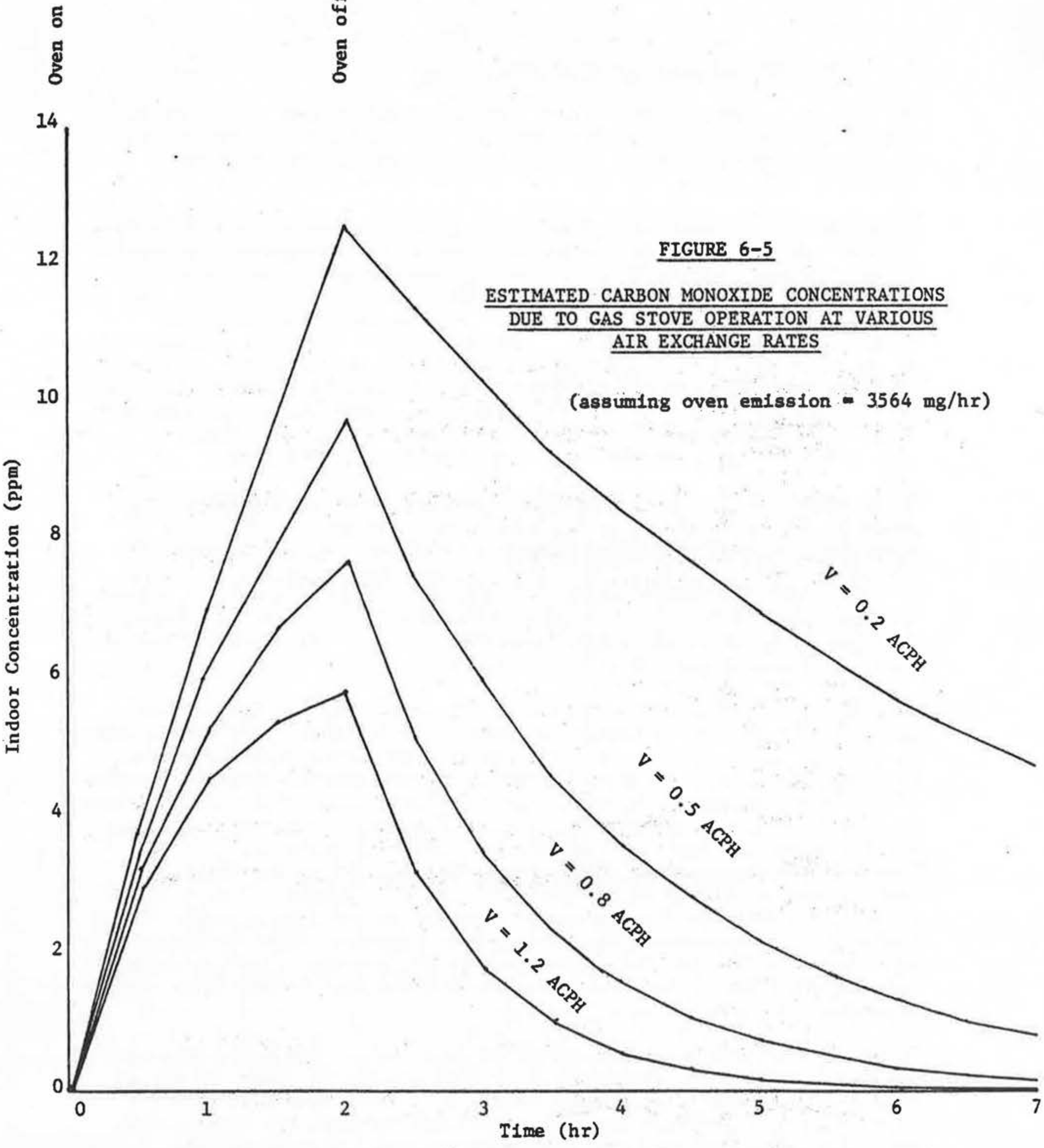

FIGURE 6-5

ESTIMATED CARBON MONOXIDE CONCENTRATIONS DUE TO GAS STOVE OPERATION AT VARIOUS AIR EXCHANGE RATES

(assuming oven emission = 3564 mg/hr)

Source: Arthur D. Little, Inc.

6.3.5 Factors Influencing Ventilation Rates

As has been noted previously, the total ventilation rate in a home is the sum of the air infiltration rate and the natural ventilation rate. It is advantageous here to reiterate briefly the factors that may influence these rates.

As discussed at length in a previous chapter, the infiltration rate into a given home is a complex function of quality of workmanship, materials of construction, condition of structure, wind direction and velocity, location and nature of leakage paths, effect of interior and exterior barriers to air flow, temperature differences, habits of occupants, presence of chimneys and vents, furnace type and operation, and humidity among other factors. The infiltration rates in one home under a particular set of environmental conditions may differ substantially from the rate in another that appears to be identical. The rate in any home will vary over a wide range from hour to hour, day to day, and season to season depending on external wind and temperature conditions.

It is important to stress that many homes may experience infiltration rates on the order of 0.1 to 0.2 air changes per hour (ACPH) under conditions of negligible wind velocity and indoor-outdoor temperature difference and that these same homes may experience rates of 1.2 ACPH or more under more severe weather conditions. Thus, the various curves on Figure 6-5 may not only be representative of conditions in a number of homes at a particular instant in time, but also may represent conditions in a single home at different times.

Natural ventilation is due to the intentional opening of windows and doors on the part of occupants to promote air exchange. The rate depends on the number and size of openings, their orientation relative to the wind direction, wind velocity, presence of interior and exterior barriers to air flow, and other factors. The combined impact of all these factors is under the direct control of building occupants, since they determine which windows and doors to open and the extent of openings. Limited research has been done to study window-opening habits, but there are certain data available on the subject. Clearly, people are most likely to open windows when the weather is pleasant and/or they strongly desire fresh air. Residences in which someone is home most days are likely to have more open windows for longer periods of time than those in which all occupants are out all day. Larger families tend to open more windows and doors than smaller ones.

It is important to note that the total ventilation rate for a home will increase dramatically whenever one or more windows or doors are opened even a small amount. In a study of a mobile home, Hunt and coworkers [13] found that one open exterior door could increase the ventilation rate to a level four to eight times the natural infiltration rate. Experiments [14] in a Chicago apartment demonstrated that the opening of windows only a quarter of an inch doubled the leakage rate under depressurization. The EPA has indicated [15] that the ventilation rate in a home with open windows and doors can typically range from 5 to 20 ACPH, noting that the average American home has an infiltration rate of 1.0 ACPH.

6.3.6 Factors Influencing Indoor Exposures

All factors discussed to this point influence the levels of contaminants to be found at various locations in a home. Essentially, it has been suggested that concentrations can vary widely depending upon the nature and strength of sources, the ventilation and decay rates, and whether the source is well-distributed or localized. This leads to the observation that the time-weighted average indoor exposure to any particular contaminant on the part of an occupant will depend on his/her choice of locations and activities in a home and the time spent in each. In other words, the spouse cooking in the kitchen for some number of hours each day is likely to be exposed somewhat differently than the spouse reading in the downstairs family room when home or the child building a model airplane in an upstairs bedroom.

6.4 IMPACT OF OUTDOOR POLLUTION SOURCES

6.4.1 Nature of Outdoor Sources

The sources of air pollution in our outdoor environment have received considerable attention in the past and are well-appreciated. They can be classified into five major source categories relating to (1) transportation, (2) domestic heating, (3) electric power generation, (4) refuse burning, and (5) industrial fuel burning and process emissions [16].

In addition, there are numerous minor sources that individually may not be significant but in aggregate cannot be considered lightly. For example, one must consider the recently identified problem relating to the use of fluorocarbons in aerosol spray cans and their potential impact on the earth's ozone layer.

Each major source has particular emission characteristics that influence its impact on outdoor air quality, and subsequently on indoor air quality. It is useful, therefore, to consider briefly these characteristics.

The bulk of emissions due to transportation activities evolve from the operation of automobiles and trucks, each of which is a mobile source of pollutants. It is well-appreciated that urban centers generally experience higher levels of pollution than rural areas due to the greater concentration of vehicles. Furthermore, it is clear that emissions from vehicles tend to peak during hours of heavy commuter traffic.

Emissions due to domestic heating with oil, gas, or wood are generated from individual homes or apartment buildings. As in the case of automobiles, greater concentrations of residences generally lead to higher levels of pollutants in the air. The overall emission rates are likely to track weather variables such as outdoor temperature and wind velocity.

Electric power generation plants using fossil fuels emit greater amounts of pollutants when power demand is high and lesser amounts when it is low. The demand is cyclic from day to day, but also has a component that fluctuates with weather conditions. Record power demands are often associated with the increased use of air conditioners, fans and refrigeration equipment during extremely hot weather.

Refuse burning has lately been confined to municipal and industrial incinerators. Small units may be operated intermittently on a batch basis. Larger ones are apt to be operated on a continuous basis.

Emissions due to industrial fuel burning for space heating purposes are somewhat likely to track those from home heating plants in a given area. Emissions related to the provision of steam or hot water for process operations, or emissions due directly to industrial processes themselves, are more difficult to characterize. They can be of a continuous nature, such as the emissions expected from a petroleum refinery, or cyclic in nature, such as those from welding or spray painting operations at an automobile assembly plant working one shift per day.

Each of the various categories of outdoor air pollution sources are associated with a variety of air pollutants. Although some of these pollutants are common to a number of source categories, others are unique and pose special problems.

6.4.2 Factor Affecting Outdoor Pollutant Levels

The concentration of a particular contaminant in outdoor air at a given location is a function of a number of variables, primarily involving weather conditions, strength and nature of nearby sources, distance to sources, source heights, and others.

Pollutants emitted into the atmosphere will mix with the air and become diluted. This atmospheric dispersion process is a strong function of the degree of atmospheric turbulence present, which in turn generally depends upon the terrain, the time of day, the wind velocity, the extent of cloud cover, and the degree of solar isolation. In very general terms, the concentration in air due to a particular source decreases with downwind distance, but the magnitude of the decrease depends on the above factors and others.

When one is interested in the impact of a given source upon a given location, the wind direction becomes extremely important. Obviously, any change in wind direction can cause a corresponding change in the downwind area subjected to pollutant emissions. Since any outdoor location is essentially surrounded by diverse pollution sources, changes in wind direction may change the relative contributions of these sources to contaminant levels at the chosen point.

The rates at which individual pollutants are released from a source are also obviously important, since downwind concentrations will vary in direct proportion to emission rates. If the upwind emission rate of a particular pollutant is doubled, then the concentrations experienced downwind will also essentially double.

6.4.3 Impact of Outdoor Sources on Indoor Air Quality

The air that infiltrates a home or that enters through an open window or door usually contains a number of contaminants in varying concentrations. Consequently, it is recognized and has been demonstrated that outdoor pollutant levels directly impact indoor air quality. Due to the complexity of the subject, it is well to consider the phenomena that may take place using four scenarios, and to assume at this time that the hypothetical home being considered does not contain indoor sources of air pollution.

The first scenario assumes that there is a constant level of a pollutant in the air outside a home, and that the pollutant is "conservative", i.e., it does not decay or otherwise disappear from the air when in contact with home furnishings. As the outdoor air enters the home over a period of time, it can fairly easily be envisioned that the indoor level of the pollutant will stabilize at the level found outdoors. The indoor level cannot be greater than the outdoor one, because it has been assumed in this scenario that all pollution sources are outdoors. It cannot be less, because it has been assumed that the pollutant is conservative. It follows that the indoor time-weighted average exposure to the pollutant will roughly be the same as the outdoor exposure.

The second scenario is similar to the first, but involves a pollutant that is "non-conservative", i.e., a substance that is adsorbed or adsorbed on internal room surface areas or decays through some other mechanism. In this case, the indoor concentration and exposure is likely to be less than that outdoors due to the decay factor.

Figure 6-6 illustrates the above phenomena for a hypothetical case in which the outdoor concentration of nitrogen dioxide is a constant 40 ppb at time zero, the air exchange rate is 1.0 ACPH, and neither the indoors nor the outdoors are contaminated prior to time zero. One curve is generated with the assumption that nitrogen dioxide does not decay and is seen to approach the outdoor level within a few hours. The other uses a nitrogen dioxide decay factor of 1.39 per hour and is seen to quickly stabilize at a indoor value of approximately 16.7 ppb. Clearly, the indoor exposure in the non-conservative pollutant case is substantially below the exposure in the conservative pollutant scenario.

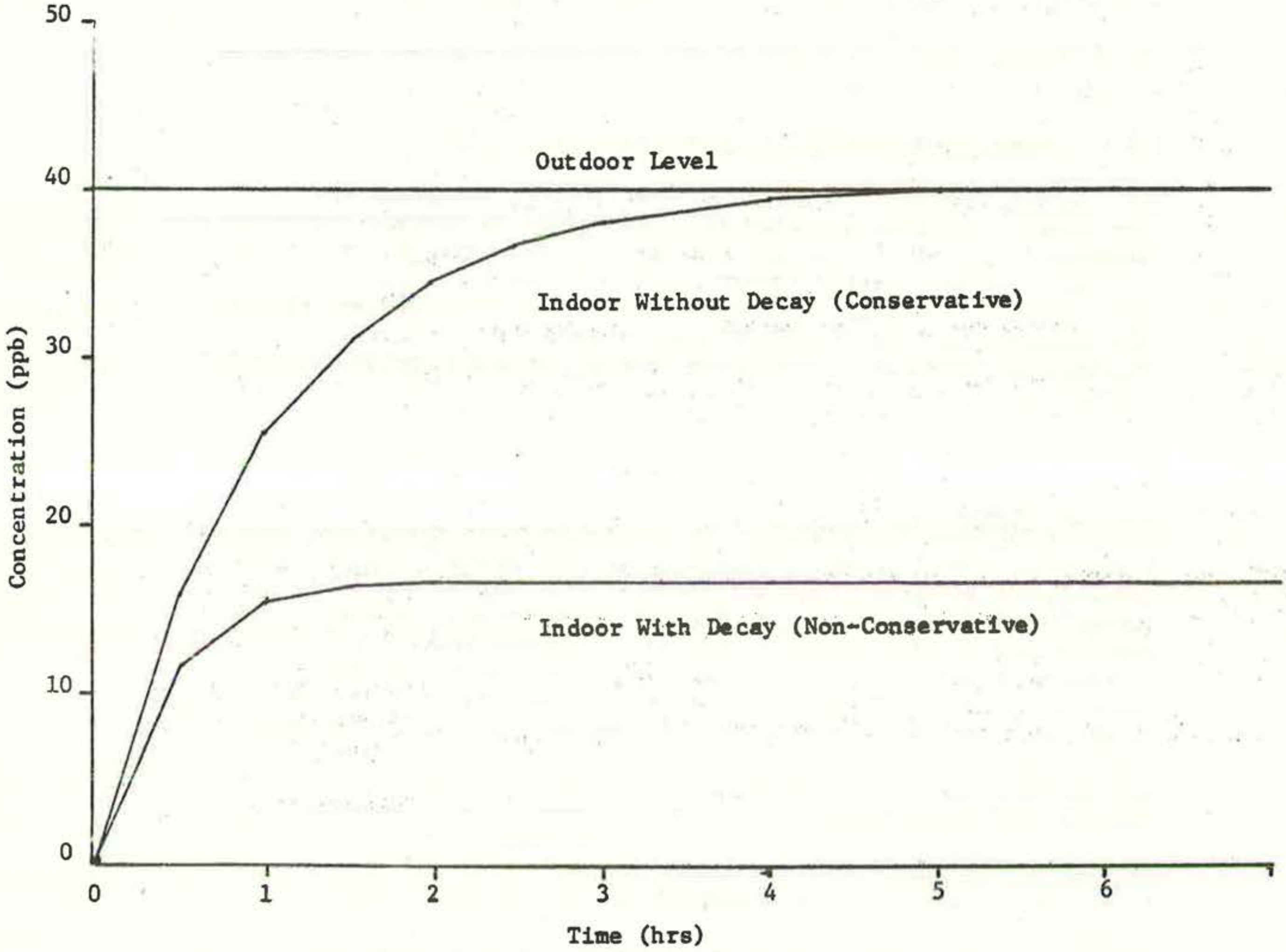

FIGURE 6-6

ESTIMATED INDOOR NO_2 LEVELS DUE TO A CONSTANT OUTDOOR SOURCE

Source: Arthur D. Little, Inc.

The third scenario considers a conservative pollutant, such as one found in automobile exhaust, with an outdoor concentration that fluctuates and has various peaks during the course of a day. It is desired to determine what effect a relatively short-lived single concentration peak will have on indoor air quality.

At one extreme, a house can be envisioned that has many wide open windows and doors such that its ventilation rate is quite high. In this case, it is self-evident that the indoor pollutant level will very closely track the outdoor level. If most or all of the windows and doors are closed, however, the ventilation rate will be substantially reduced. As the concentration spike passes the house along with the wind, internal spaces will experience a peak concentration that is considerably below the outdoor peak level, but <u>the time-integrated exposure of occupants</u> will again be essentially the same.

Figure 6-7 presents the results of a computer simulation by GEOMET involving the passage of a single outdoor concentration spike of carbon monoxide and showing the effect of reducing the air exchange rate in a residence without indoor sources of this contaminant. Note that as the peak indoor concentration is reduced with decreasing air exchange rates, the width of the spike increases. Table 6-2 presents the estimated exposure for each of the curves. As expected, it demonstrates that changes in the air exchange rate have minimal impact on <u>exposures</u> due to outdoor pollutant sources.

It is important to understand the phenomena that take place to cause this behavior. As the leading edge of what can be called the pollutant "cloud" reaches the home and begins to pass over it, the rate at which the contaminant enters the house with outdoor air increases. Since the walls of the home act as a barrier to flow, however, the rate is less than it would be if the walls were not present or all windows and doors were open. Thus, the build-up of the indoor level is retarded and the concentration peaks at a lower level than outdoors.

After the trailing edge of the outdoor cloud passes the house, cleaner air will begin to enter and dilute remaining indoor pollutant concentrations. Since the rate of ventilation is still reduced, the drop-off or "purging rate" will also be slower than it is outdoors. It can be shown that the additional time required for indoor levels to reach a peak and drop-off to original levels counterbalances the benefit of a reduced peak level. This occurs to the extent that time-weighted average indoor exposures may approximate those outdoors.

When the pollutant is non-conservative and an outdoor peak occurs, indoor levels will follow the same general trend described directly above. However, since decay takes place, they will be somewhat lower than those associated with conservative pollutants and the indoor exposure will be less than outdoors. Both indoor concentrations and exposures will be a function of the ventilation rate as in the scenario considered above.

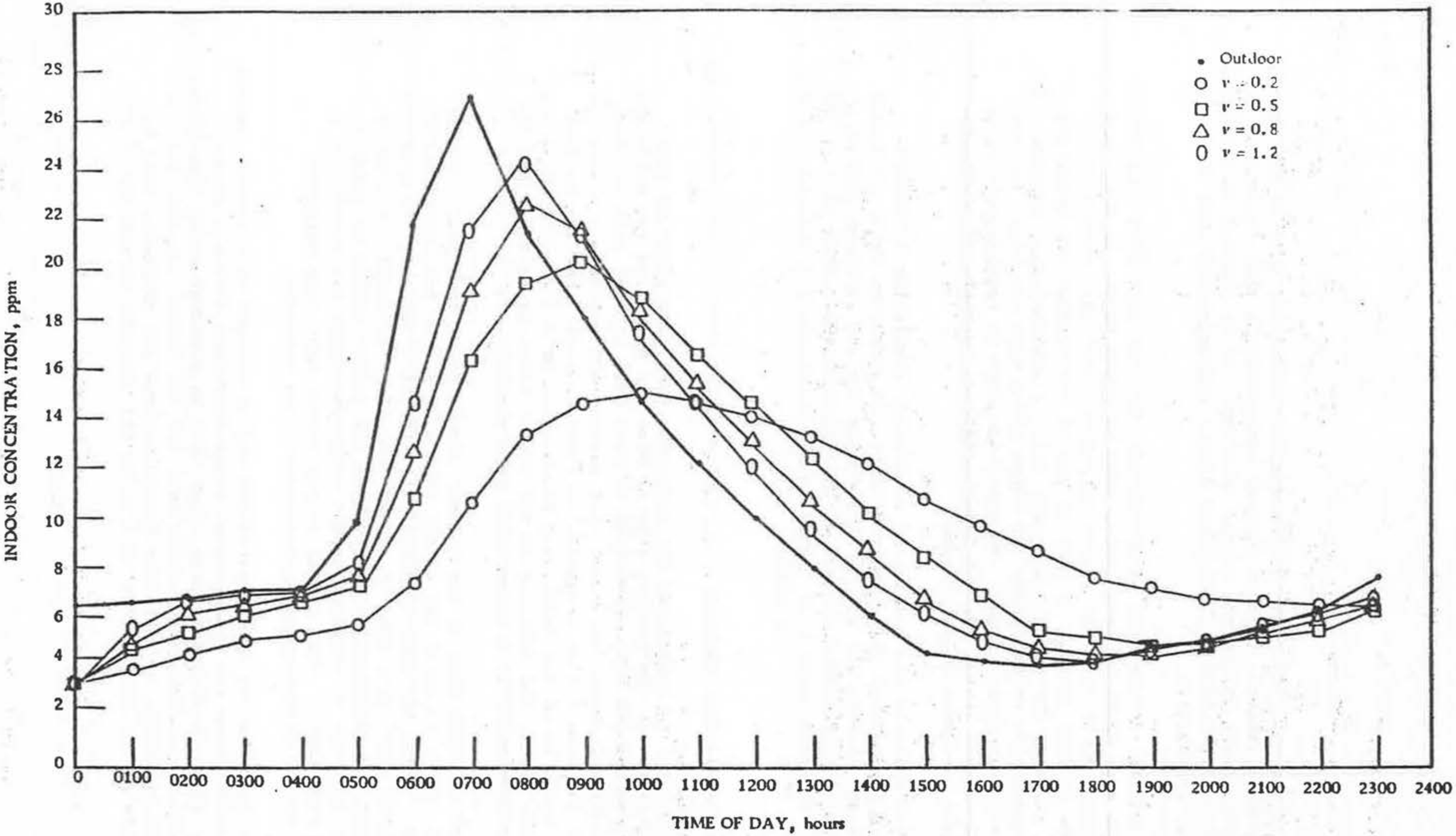

Figure 6-7: Effect of reducing the air exchange rate in a residence without indoor CO sources. [7]

TABLE 6-2

ESTIMATED INDOOR CARBON MONOXIDE EXPOSURES
WITH NO INDOOR SOURCES [7]

Air Change Rate	Exposure (ppm-hours)
Outdoors	226
1.2	223
0.8	222
0.5	221
0.2	210

6.4.5 Factors Influencing Exposures

Previous discussion has addressed factors that influence indoor pollutant concentrations due to indoor pollutant sources and those that impact upon the exposures received by individuals. Factors were described that determine the pollutant concentrations at points outdoors due to external pollutant sources, and it was demonstrated how outdoor concentrations can impact indoor air quality. It should be noted that the overall exposure of an individual to a particular contaminant will also depend to a great extent on the amount of time spent at each of the various indoor and outdoor locations visited during the course of a day, especially if there are considerable differences in pollutant levels.

6.5 COMBINED EFFECTS OF INDOOR AND OUTDOOR POLLUTANT SOURCES

6.5.1 Conservative Pollutants

It has been demonstrated that indoor exposures due to outdoor sources of conservative pollutants such as carbon monoxide, nitric oxide, carbon dioxide and other substances are an extremely weak function of ventilation rates. One can justifiably conclude from this and other findings that changes in home infiltration rates will have a minimal impact on indoor pollutant exposures when the source of pollutant is outdoors and the pollutant is conservative. However, such changes do impact peak concentrations, with lower infiltration rates leading to lower peak concentrations and higher rates leading to higher peak concentrations.

When the source of conservative pollutant is indoors, the rate of ventilation is highly influential in determining the indoor exposure and the magnitude of any peaks that may be experienced. The indoor exposure under relatively high ventilation rates will be a small fraction of the exposure under low ventilation rates.

When conservative pollutants are generated indoors and outdoors, the combined indoor exposure due to all sources is essentially the sum of all parts. Figure 6-8 from the GEOMET study [7] demonstrates the average indoor concentrations expected due to the combined effect of indoor and outdoor sources of carbon monoxide for a number of different air exchange rates. The peaks on the left are mostly attributable to an outdoor source. Those on the right are mostly due to gas stove and oven usage.

Table 6-3 lists the estimated exposures due to the conditions modeled in Figure 6-8 when (1) only outdoor sources are considered; (2) when only indoor sources are considered; (3) when both indoor and outdoor sources are considered. Clearly, in this hypothetical scenario which GEOMET implies is not unrealistic for conditions in Los Angeles, the contribution of indoor sources is smallat an infiltration rate of 1.2 ACPH, yet significant at a rate of 0.2 ACPH. It is noteworthy that the contribution of the indoor source would be truly minor if one or more windows and doors were open in the home and the total ventilation rate was in the typical range of 5 to 20 ACPH.

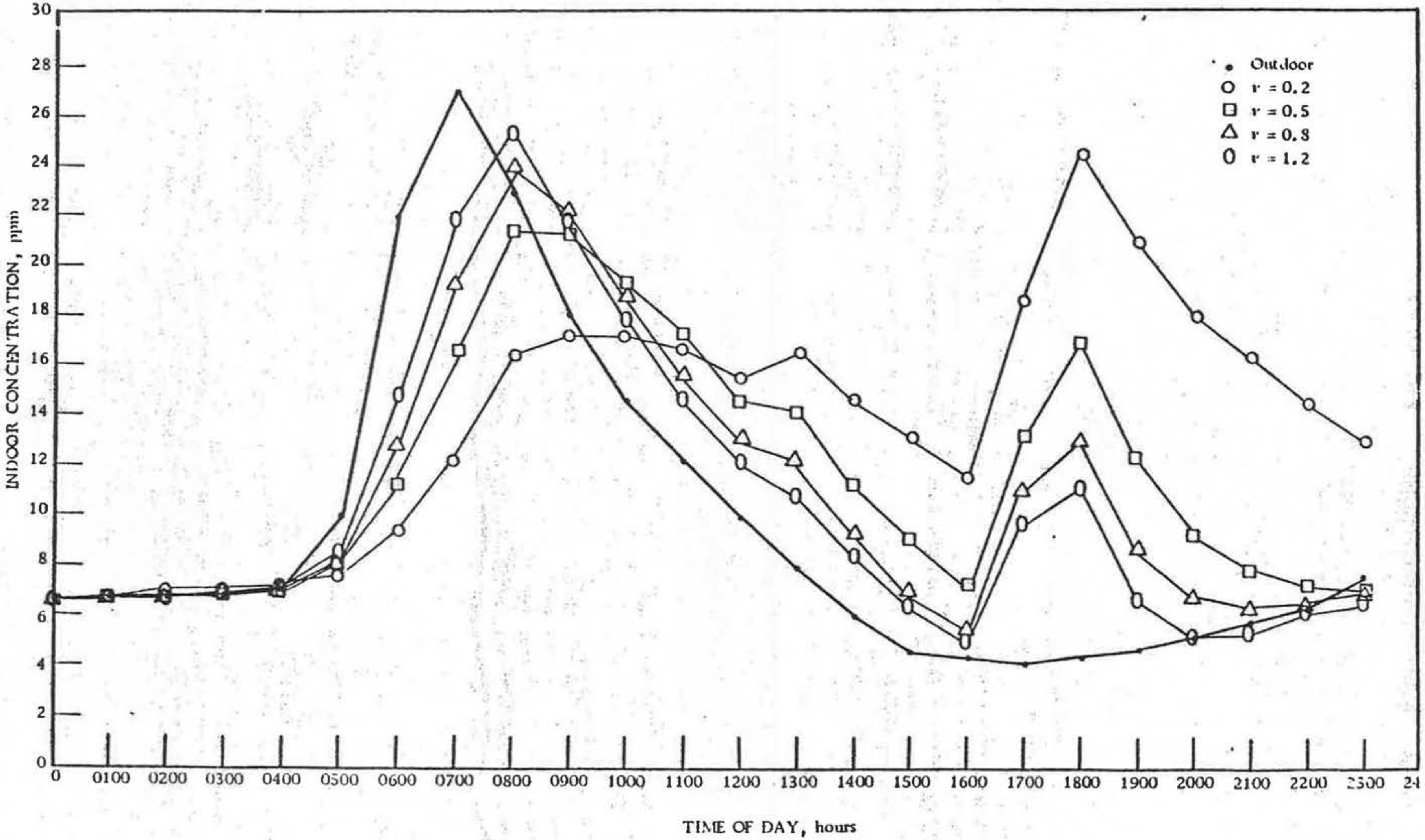

Figure 6-8: Effect of reducing the air exchange rate in a residence with indoor CO sources [7].

TABLE 6-3

ESTIMATED INDOOR CARBON MONOXIDE EXPOSURES [7]

	24-Hour Exposures (ppm-hours)		
Air Change Rate	Outdoor Source	Indoor Source	All Sources
Ambient (outside)	226		
1.2	223	24	247
0.8	222	36	258
0.5	221	54	275
0.2	210	110	320

6.5.2 Non-Conservative Pollutants

Non-conservative pollutants such as nitrogen dioxide, ozone, and sulfur dioxide decay in the presence of home furnishings. Table 6-4 illustrates the impact of changes in ventilation rate on indoor exposures when the pollutant is not generated indoors by using the mass balance equations and assuming (1) a constant outdoor nitrogen dioxide concentration of 40 ppb; (2) a house volume of 15,000 cubic feet; and (3) a decay factor of 1.39 per hour. Clearly, reduced ventilation rates in this case result in decreases in indoor concentrations and exposures. This contrasts with the conservative pollutant case where reduced rates had minimal impact on exposures.

When a non-conservative pollutant is generated indoors, the situation is somewhat analogous to the one for conservative pollutants. Increased ventilation rates will lead to lower exposures and reduced rates will cause increased exposures. The magnitudes of concentrations and exposures will not be quite as sensitive to changes in the ventilation rate, however.

Table 6-5 is the result of using the mass balance equations to test the sensitivity of indoor concentrations to changes in ventilation rates. Based on assumptions of a continuous indoor source of pollutant and a one mass unit per unit time generation rate, the table presents multiplicative factors showing relative indoor concentrations for nitrogen dioxide and carbon monoxide. The results suggest that indoor nitrogen dioxide concentrations under these steady-state conditions would increase by 162% if the ventilation rate were decreased from 1.2 ACPH to 0.2 ACPH. Carbon monoxide concentrations under similar circumstances would increase by roughly 600%. Thus, it is evident that the adverse effect of reducing ventilation rates can be substantially more severe in the case of a conservative pollutant than a non-conservative one.

In a simulation similar to the one for carbon monoxide, GEOMET looked at the effect of gas stove operation on nitrogen dioxide exposures in a typical home. Assuming an outdoor 24-hour exposure of 4188 ug/m^3 - hours, it found that the indoor exposure would range from 2067 to 2873 ug/m^3 - hours as the ventilation rate changed from 0.2 to 1.2 ACPH. For a home without a gas stove, it estimated a range of 479 to 1972 ug/m^3 - hours under similar conditions. It is quite significant that indoor exposures were always substantially less than those outdoors regardless of the specific ventilation rate applied.

6.5.3 Summary of Findings

The preceding analysis has indicated that there are both advantages and disadvantages to any envisionable changes in home ventilation rates. Table 6-6 summarizes findings in a matrix that considers whether ventilation rates are increased or decreased and whether pollutant sources are indoors or outdoors. Inspection of the matrix can clarify why the

TABLE 6-4

ESTIMATED INDOOR NO_2 EXPOSURES

Air Change Rate	Indoor Concentrations* (ppb)	24-Hour Exposure (ppb-hr)
1.2	18.53	444.7
0.8	14.61	350.6
0.5	10.58	253.9
0.2	5.03	120.7

*Outdoor concentration is assumed to be 40 ppb.

Source: Arthur D. Little, Inc.

TABLE 6-5

SENSITIVITY FACTORS FOR CONSERVATIVE AND NON-CONSERVATIVE POLLUTANTS

Air Change Rate	NO_2	CO
0.2	0.63	5.0
0.5	0.53	2.0
0.8	0.46	1.25
1.2	0.39	0.83
Percent*	162	602

*Percentage indoor concentration increase expected if ventilation rate is reduced from 1.2 to 0.2 ACPH.

NOTE: These are results for steady-state conditions. Results for intermittent activation of indoor pollutant sources may differ somewhat. Outdoor concentrations are taken to be zero.

Source: Arthur D. Little, Inc.

TABLE 6-6

SUMMARY OF FINDINGS VIS-A-VIS INDOOR AIR QUALITY

Pollutant Type	INDOOR SOURCES: Impact of Reduced Ventilation	INDOOR SOURCES: Impact of Increased Ventilation	OUTDOOR SOURCES: Impact of Reduced Ventilation	OUTDOOR SOURCES: Impact of Increased Ventilation
Conservative	Bad. Significant increase in exposure and concentrations.	Good. Significant decrease in exposures and concentrations.	Somewhat good. No. major impact on exposures, but decreased peak concentrations experienced.	Somewhat bad. No major impact on exposures, but increased peak concentrations experienced.
Non-Conservative	Somewhat bad. Moderate increase in exposures and concentrations, but indoor conditions may still be better than those outdoors	Good. Moderate decrease in exposures and concentrations.	Good. Can be significant decrease in exposures and concentrations.	Somewhat bad. Can increase in exposure and concentrations, but indoor conditions may still be better than those outdoors

Source: Arthur D. Little, Inc.

entire subject area of reduced infiltration rates and indoor air quality is controversial and difficult to address in a manner that results in clear-cut solutions. Reduced ventilation rates have adverse impacts on indoor exposures and concentrations when the source is indoors, and generally beneficial impacts when the source is outdoors. Conversely, reduced rates can lead to lower energy usage and lower pollution emissions from home furnaces. Increased ventilation rates have almost an exactly opposite effect in every case.

The issues raised become substantially more complicated when one attempts to define the health impacts of ventilation rate changes in homes. Since any change may increase exposures to one set of contaminants, i.e., those generated indoors or outdoors, while decreasing exposures to another set, and since the "mixture" of contaminants generated indoors differs from the mixture generated outdoors, there are certain tradeoffs involved that are difficult to assess.

6.6 QUESTIONS REQUIRING STUDY

6.6.1 Objectives

Over recent years there has been considerable research devoted to the study of indoor air quality, with special attention to particular aspects of the overall problem. Previous chapters of this report have reviewed these efforts and summarized their results. In the following, an attempt is made to redefine the various questions that must be answered in order to fully assess the impact of indoor air pollution upon public health. This will ultimately set the stage for the development of specific recommendations for future research into the particular problems due to unvented gas-fired appliances if and when home infiltration rates are reduced for energy conservation purposes.

6.6.2 Infiltration and Natural Ventilation

There is a particular aspect of the problem relating to current ventilation rates in homes that does not appear to have been previously addressed in a forthright fashion. Its identification evolves from the very basic observations that:

1. Ventilation rates in homes with open windows or doors are substantially greater than infiltration rates.

2. For a number of months each year, virtually every part of the country experiences weather conditions conducive to the opening of windows for cooling purposes or simply for fresh air.

3. The exposures inside homes with high ventilation rates will closely resemble those experienced outdoors.

4. Infiltration rates in homes during winter are substantially higher than summer rates and well-above the average rates experienced on an annual basis.

These observations lead to the questions:

Question No. 1: By region of the country and by season, what is distribution of homes with open windows as a function of time?

Question No. 2: Is it reasonable to assume that there are no significant indoor air quality problems due to indoor pollutant sources when windows and doors are open in a home?

Question No. 3: If the answer to question No. 2 is "yes" or a qualified "yes", what fraction of time on a yearly basis do individuals in each region of the country typically spend in a home with closed windows and doors?

Question No. 4: What is the distribution of actual infiltration rates experienced in homes when windows and doors are closed and one or more residents are home?

Question No. 5: How would the distribution identified in question No. 4 change if all existing homes were retrofitted with the most common measures to reduce infiltration rates and new homes are built to "tighter" specifications?

In many regions of the country, such as New England, typical inhabited homes are likely to have one or more open windows almost continuously from late spring through early autumn. The above questions are intended to determine the remaining fraction of time in which residents are home and windows and doors are closed. Additionally, they are intended to determine what the actual infiltration rates are at such times and to assess the impact of retrofitting existing homes.

6.6.3 Outdoor Source Impacts

Indoor exposures are directly related to outdoor pollutant levels. Subsequently, the enforcement of limits on average national exposures to specific contaminants makes the impact of indoor sources more critical.

Question No. 6: On a contaminant-specific basis, and by region of the country, how much leeway is there between air quality standards and exposures experienced outdoors. (See Question No. 12 also.)

Question No. 7: What is the difference, if any, in outdoor exposures between time periods when home windows and doors are likely to be closed and time periods when they are more likely to be open? (See Question No. 12 also.)

Question No. 8: Are national air quality standards fully supportable and reasonable based on the most current available data?

Question No. 9: What contaminants in outdoor air are not covered by national ambient air quality standards? At what levels are they capable of causing adverse health impacts?

Question No. 10: Are some air quality standards more important to meet than others?

Question No. 11: What options are available to reduce outdoor exposures? What are their costs, benefits, and adverse impacts?

6.6.4 Indoor Source Impacts

It is not altogether clear in some cases whether a particular indoor source of pollutant is significant in terms of health effects upon the general population when it is released into the air at times that home windows and doors are closed. Thus, there is a need to determine the potential effect of proposed reduced infiltration rates upon indoor and total exposures and to identify those contaminants and their sources that are most likely to pose health threats.

Question No. 12: What are the characteristics of the overall exposures (individual and total of all indoor and outdoor elements) currently experienced in the various regions of the country as a function of season?

Question No. 13: What contaminants in indoor air are not covered by national ambient air quality standards? At what levels are they capable of causing adverse health impacts?

Question No. 14: How would total exposures change if the distribution of infiltration rates identified in question No. 5 came into being?

Question No. 15: Which of these exposures are excessive in terms of acknowledged health effects or ambient air quality standards?

Question No. 16: Among those that are excessive, which are primarily due to pollutant sources in the home?

The basic approaches to reducing indoor exposures due to indoor sources include:

1. Increased dilution through increased ventilation;
2. Removal of contaminants using air cleaning devices or exhaust systems;
3. Placing limits on source strengths; and
4. Elimination or containment of the source.

Each approach has particular advantages and disadvantages when applied to the source(s) of a particular contaminant. Some are simultaneously applicable to a number of sources, while others are best suited to a particular type of source. Consequently, it is necessary to study available control strategies with the objective of identifying those that are optimal in terms of cost and overall efficiency.

Question No. 17: What are the characteristics of the various sources of pollutants identified in question No. 16?

Question No. 18: What are feasible control strategies for each individual source?

Question No. 19: What would be the costs, benefits, and adverse impacts of implementing the control strategies identified above on a national basis.

6.6.5 Development of Overall Strategy

The indoor air quality problem is one element of a larger problem area encompassing exposures to airborne toxic agents in the home, outdoors, and in the occupational environment. Consequently, the 19 questions asked above were specifically chosen to demonstrate what must be known for the development of a comprehensive and optimally cost-effective strategy for approaching the problem. Thus, the final question becomes:

> <u>Question No. 20</u>: Given the information generated in efforts to answer the above questions, what is the best overall strategy for addressing the specific exposures identified in answer to question No. 15?

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7. RECOMMENDATIONS FOR RESEARCH AND DEVELOPMENT CONCERNING INDOOR AIR QUALITY

7.1 . INTRODUCTION

Although a considerable amount of research has been conducted in the area of indoor air quality, the problem has not been resolved. In fact, the actual nature and extent of the problem has not been adequately defined. In order to promote a coordinated research effort on the Federal level, an Interagency Research Group on Indoor Air Quality was established and in December of 1980; a Workshop on Indoor Air Quality Research Needs was sponsored by the Environmental Protection Agency (EPA), Department of Energy (DOE), Department of Housing and Urban Development (HUD), Consumer Product Safety Commission (CPSC), and the National Institute for Occupational Safety and Health (NIOSH). An outline of research elements developed by the Interagency Research Group is shown in Table 7-1 and covers five general areas: (1) Monitoring and Pollutant Characterization, (2) Instrumentation, (3) Health and Welfare Effects, (4) Risk Assessment, and (5) Control Technology.

While the research interests of the Gas Research Institute are more circumscribed than those of the Interagency Research Group, they seem to include those five general topics. Subsequent discussions will address each of these areas and will identify research needs which appear to be consistent with the interests of the Gas Research Institute. Currently the Gas Research Institute is developing an Environmental Research Plan for Gas Utilization Technologies which will address the generic issue of indoor air. It is hoped that the research needs identified here will be incorporated into the Research Planning process.

7.2 MONITORING AND POLLUTANT CHARACTERIZATION

There is a need for the development of improved methods for the collection and analysis of samples. The most immediate need is to evaluate existing personal monitors, particularly passive devices, and to make any necessary improvements. A relatively new area is the development of non-invasive biological sampling methods (e.g., analysis of hair, urine, and breath) for field exposure studies; however, biological sampling is more relevant for evaluating absorption and ingestion than inhalation.

A considerable amount of work has been done in the area of modeling, however, there is a need for models of personal activity patterns which can then be used to improve exposure profiles. Input data for modeling could be collected through surveys of gas appliance users to determine patterns of use, misuse, use of range hoods and other control devices, and behaviors and conditions related to the use of these appliances. Such a survey could also be used to investigate trends toward reducing air infiltration. In addition, the data could be used to estimate the nature and size of the potential population at risk. For example, a relevant question is how many asthmatics or persons with chronic respiratory disease operate unvented gas appliances in tight houses or confined spaces? Alternatively,

TABLE 7-1

SUMMARY OF RESEARCH ELEMENTS

Monitoring and Pollutant Characterization

- indoor air quality characterization
  --controlled conditions (experimental buildings)
  --field monitoring (real-life conditions)
- hazardous pollutant identification
- source assessments
- total exposure

Instrumentation

- testing and evaluation of existing instruments
- improvement of existing instruments
- development of new instruments
  --personal monitors
  --stationary monitors
  --for pollutants where no methods exist
- development of measurement protocols
- development and implementation of a quality assurance program

Health and Welfare Effects

- comparison of pollutant characterization data with known health effects
- health effects studies
  --laboratory toxicological studies
  --epidemiological studies
- welfare effects studies
  --corrosion, abrasion, soiling, etc.

TABLE 7-1 (Cont.)

Risk Assessment

- determination of health risk for various populations and conditions
  --short-term
  --long-term

Control Technology

- engineering analysis of options and establishment of priorities based on risk
- development and assessment of controls
  --radon
  --asbestos
  --formaldehyde
  --others
- development of integrated systems for major building categories and pollutants
- analyses of cost-effectiveness
- development of educational program for building occupants

SOURCE: Interagency Research Group on Indoor Air Quality do asthmatics alter their behaviors and activity patterns (e.g., window-opening) to reduce their exposure to outdoor and indoor pollutants?

There continues to be a need for field studies which quantify personal exposure and which can determine the relative contributions of indoor and outdoor sources. GRI could play an important role by entering into cooperative agreements with the EPA and DOE to support on-going and future monitoring studies such as the Six Cities Study. These studies require long periods of time, substantial funding, and can not be reasonably undertaken by any single organization. An important topic of interest for the Gas Research Institute is the monitoring and characterization of oxides of nitrogen in the indoor environment. Basic research is needed to characterize emissions, the conversion of NO to NO_2 and their ultimate decay and fate in the indoor environment.

7.3 INSTRUMENTATION

Research needs for instrumentation include the development and validations of sampling and analytical methods and the development and evaluation of instrumentation for the monitoring and control of indoor air pollutants. Specific instrumentation research needs which are relevant to the interests of GRI include the following:

- Carbon monoxide monitors which use the gas bag-infrared procedure are limited in utility because they cannot store samples.

- The accuracy of solid sorbent-spectrophotometry methods for sampling nitrogen dioxide and nitric oxide needs to be determined.

Research to characterize oxides of nitrogen should provide the foundation for developing accurate and precise monitoring instruments which are relatively inexpensive and which can be used to quantify personal exposures.

7.4 HEALTH AND WELFARE EFFECTS

Future research in the area of health and welfare effects is likely to consist of large-scale studies such as the Six Cities Study which will combine monitoring of total exposure on a 24-hour basis with quantitative assessment of health effects. As in the case of monitoring studies, GRI is not likely to undertake such studies as a sole sponsor but could enter into cooperative ventures with other public or private organizations. On a national level it appears that the major foci of interest for health effects research will be radon, formaldehyde, organics such as 1,4-dichlorobenzene and pentachlorophenol, and biological contaminants, while for GRI the focus should be oxides of nitrogen.

There is a large data base derived from experimental human exposure studies which has not been subjected to review and analysis. The dose-response relationships developed in these studies are conflicting and yet some of the data has been used tc justify standards. Therefore, a research need is a comprehensive review of experimental human exposure studies to determine the statistical validity and physiological or epidemiological relevance of the results.

7.5 RISK ASSESSMENT

This study was cited at the Interagency Workshop as being one of the few examples of indoor air quality risk assessment. Although this study does not present quantitative estimates of risk, it is consistent with the objective of the Health Risk Analysis Program which is "to strengthen the basis for planning and contracting research and development programs by analyzing current knowledge and uncertainty regarding the potential health consequences of indoor air pollutants. [1]

This comment leads naturally to the recommendation that the current study be continued for the purpose of continual data collection and review of issues related to indoor air quality. The recent symposium at the New York Academy of Medicine and the upcoming international symposium indicate that a considerable amount of research is being conducted and the results should be reviewed and incorporated into this report. Eventually, it is hoped that studies such as the Six Cities Study will develop sound risk parameters such as dose-response relationships which can be utilized for quantitative risk assessment.

Research in the area of risk assessment should include studies of the cost-effectiveness of alternative controls and the relative costs and benefits to society of various levels of control. A particularly important question is the costs and benefits of environmental health programs which seek to protect the most sensitive members of the population. In a cost-benefit analysis this approach would be contrasted with a program which seeks to protect the majority of the population while encouraging sensitive persons to initiate additional protective measured in accordance with their individual needs and susceptibilities.

7.6 CONTROL TECHNOLOGY

There are various approaches and combinations of approaches for control technology which include:

- Ventilation including forced or mechanical, passive or natural, and unintentional or infiltration. Efficiencies of ventilation control strategies and their energy costs need to be studied.
- Source control may involve modification of burner design, electronic pilot lights, or appliance-specific exhaust systems.
- Contaminant control may be achieved with pollution control devices such as electrostatic precipitators or with ventilation techniques.

- Human factor control uses educational approaches to inform residents of potential hazards and encourage behaviors that will reduce pollutant exposure.

- Warning devices may be activated by contaminant levels or temperature and may be designed to prompt preventive behavior (e.g., smoke alarms), to activate controls, or to cut off sources.

Specific control technology research areas include the following:

7.6.1 Vented Range Hoods

A typical range hood vented to the outdoors has the potential to reduce contaminant emissions to the indoor environment by approximately 40 to 50% or more when activated above an operating gas stove. Critical factors in determining efficiency include hood design, placement, and exhaust volume provided; improvements in efficiency are most likely achievable by refinement of current designs. Use can be encouraged by ensuring quiet operation. Some thought might be given to automatic activation directed by a control unit with a temperature or contaminant sensor or by an interlocking mechanism integrated with burner controls. Since venting heated air results in energy loss, there is a need to develop cost-effective mechanisms for heat recovery from exhaust air.

A possible problem with vented range hood use in a home highly resistant to infiltration would be a loss of hood efficiency from a lack of make-up air. Alternatively, powered ventilation systems may result in the reversal of natural draft vents such as the chimney. There may be some benefit therefore in the development of a venting system that simultaneously provides fresh air to the kitchen while exhausting contaminated air. A more likely problem is the loss of energy associated with venting air to the outside. Fowell [2] describes an adaptable concept for clothes dryers in which the exhaust duct is placed within a larger duct conveying outdoor air in the opposite direction, and there is some degree of heat recovery. Mitsubishi is reported to be working on a similar concept for kitchen exhaust purposes. Considering that the air being exhausted is very likely to be warmer than the average temperature of the indoor air, and that operation of the appliance will tend to heat up the kitchen, there is potential here for exhaust of contaminated air with little or no additional discomfort caused by inlet of possibly cold outdoor air.

7.6.2 Unvented Range Hoods

A recirculating type of range hood has two primary advantages. It can be installed without the expense of a vent to the outdoors. In addition, it does not promote air infiltration. Disadvantages include non-removal of excess heat or humidity, and the possibility for some models of little or no efficiency in regard to removal of certain gaseous contaminants from the internal environment. Nevertheless, the basic concept of such devices appears to be essentially sound, and their effectiveness may be enhanced by application of modern air pollution control technology, including the development of inexpensive disposable or reusable filters.

7.6.3 Oven Vents

For a time period prior to 1950, standards by ANSI and the AGA required manufacturers to make vented gas ovens available if they were so requested by customers. The standards were dropped in 1950 because of a lack of consumer demand which was primarily associated with the need for additional space for proper installation of the draft diverter [3]. There is a possibility that a new look at the subject area might result in techniques to vent stoves without the features that made this practice unattractive to consumers in the past.

7.6.4 Electric Ignition Systems

Although continuous-burning pilot lights are not a major source of indoor air pollutants, they do contribute to the overall indoor levels. Furthermore, it is well-appreciated that pilots in ranges account for 30 to 40% of gas consumption, and for similar significant percentages in other appliances. This source of pollutants could be deleted from consideration if all new gas appliances were fitted with intermittent ignition devices (IID's) and if a concerted effort took place to retrofit existing appliances with IID's in homes with low to moderate infiltration rates. Questions related to the reliability and safety of such devices should be investigated before they are advocated on a widespread basis.

Cox and Kornguth [4] provide an excellent review of the subject area in the context of energy conservation.

7.6.5 Redesign of Equipment

Various references in the literature point to the fact that the specific design of a burner and its ancillary devices can impact upon the emission rates of individual pollutants. Further research in this area may lead to significant reductions in the emission rates for pollutants that are determined to be a problem. In some cases, redesign of appliance components could lead to less likelihood of "spillage" of contaminants into the indoor environment.

7.6.6 Increased Ventilation

It is not unusual for homes with gas furnaces to have gas ranges and vice versa. Moreover, it is common for heating or air-conditioning systems to be of the forced-air type. Among the major pollutants in indoor air are many contaminants primarily evolved from non-combustion related processes.

One frequently discussed concept for controlling the levels of <u>all</u> air contaminants generated indoors involves increased fresh air ventilation, typically in association with an air-to-air heat recovery unit of some sort to reduce heating and cooling energy losses. This could be accomplished in new homes by designing the HVAC system so that fresh air is continually drawn into the home at a predetermined rate and an equal amount of the return air supply is simultaneously exhausted. Researchers [5] have estimated that energy losses would be more than offset by savings due to reduced infiltration rates in tightly constructed homes.

7.6.7 Appliance Usage Guidelines

There will be circumstances in which an appliance, particularly an unvented appliance, should not be used due to lack of adequate space or ventilation. There may be benefit in better delineation of these circumstances with a view to discouraging pollutant-emitting appliance use where appropriate safeguards have not been taken.

7.6.8 Use of Air Cleaners

Previous discussion addressed the possibility of using contemporary air pollution control technology to enhance the effectiveness of recirculating exhaust hoods in homes with low infiltration rates. Additionally, the concept of increased fresh air ventilation rates using control forced-air HVAC systems and air-to-air heat recovery devices was suggested. Combination of these two approaches would call for a completely recirculating central HVAC System with an integral air cleaning section for particulate matter and important vapors and gases.

7.6.9 Warning Devices

In the majority of normal homes, excessive contaminant levels due to gas-appliance use are only likely when lengthy operation is coupled with low air infiltration rates. It is worthwhile, therefore, to consider the development of a reasonably priced alarm device that can warn occupants of possible unhealthy conditions or that can activate exhaust systems. In order to assure that filtration systems operate effectively, it would be useful to develop an end-of-service-life indicator.

7.7 CONCLUSIONS

A variety of research needs concerning indoor air quality have been identified. While it is expected that the Environmental Research Plan for Gas Utilization will address the relative levels of effort and scopes of work which should be undertaken, it is appropriate at this time to address research priorities.

A most important issue is to characterize quantitatively personal exposure to oxides of nitrogen in the residential environment and to distinguish quantitatively between exposure to nitric oxide and nitrogen dioxide. Subsequently, it will be necessary to determine the adverse health effects of exposure to those levels and to distinguish between responses which are adaptive or protective in nature and responses which reflect pathological changes.

Because of the significance attached to the results of experimental human exposure studies, a review and analysis should be conducted to determine the relative toxicities of nitric oxide and nitrogen dioxide. This review should focus on recent studies or studies which are considered to be significant and should determine the validity of the exposure and response measurements and the relationship between the response and any actual or potential adverse health effect. If the actual types of personal exposures experienced in the indoor environment can be associated with adverse health effects, an appropriate step would be the identification of populations for epidemiological research. A prospective study would be preferable because it allows the quantification of exposure and direct calculation of incidence rates. The advantages of reduced cost and time associated with retrospective studies would not be warranted in this case because the assessment of exposure is crucial.

Research related to instrumentation for monitoring oxides of nitrogen is also a high priority while the importance of control technology research will depend upon the levels of risk identified in research related to health effects.

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8. AIR QUALITY STANDARDS

8.1 INTRODUCTION

Before the potential role of indoor residential air pollution as a public health problem was fully recognized, areas of prime concern vis-a-vis air quality included the outdoor environment and the indoor occupational environment. In the United States and elsewhere throughout the world, regulatory agencies and others with a role in promoting healthful living and working conditions promulgated various standards and criteria which designated the airborne levels or exposures to specific toxic agents that were to be considered as the borderline between safe and unsafe conditions. These various standards and criteria are reviewed in the following sections with the objective of investigating their suitability for application in the indoor residential environment, a realm for which many of them were not originally intended. Also considered is the question of the jurisdiction of regulatory authorities in the United States.

An excellent source of information on the entire subject area is a 1978 study by McFadden, Beard, and Moschandreas [1] for the U.S. Environmental Protection Agency (EPA). Although this chapter includes many major conclusions of their work, and indeed borrows heavily from its contents, the interested reader is referred to their final report to the EPA for further details. For data on occupational exposure limits and their formulation, Reference 2 is recommended. Similarly, Reference 3 is recommended for those wishing to review a detailed discussion concerning the problems and uncertainties associated with current air quality criteria.

8.2 STANDARDS AND CRITERIA OF DOMESTIC REGULATORY AGENCIES AND ORGANIZATIONS

8.2.1 U.S. Environmental Protection Agency (EPA)

Section 107 b1 of the Clean Air Act of 1967 (42 U.S.C. 1857-2b1) delegated authority to the Commissioner of the National Air Pollution Control Administration to develop air quality criteria documents, i.e., descriptions of the relationship between pollutant concentrations in air and their effects, if any, on man and his environment. Subsequently, the Clean Air Act of 1970 and its amendments called for the promulgation of national air quality standards for six air pollutants on the basis of available data. This latter task was delegated to the Administrator of the then newly created Environmental Protection Agency (EPA).

The criteria documents that resulted were based on research data including epidemiological studies, observed industrial responses to pollutant exposures, observed human responses in laboratory or chamber environments, and animal studies. Data from both indoor and outdoor environments were considered, although the subsequent standards applied to that portion of the atmosphere, exclusive of buildings, to which the general public has access. These standards, with the force of law, were published in the Federal Register of April 30, 1971 and are summarized in Table 8-1.

8.2.2 American Conference of Governmental Industrial Hygienists (ACGIH)

Although not a governmental body per se, the ACGIH has had widespread impact on occupational exposure standards in the U.S. and elsewhere through its process of promulgating Threshold Limit Values (TLV's) for substances in workroom air. These TLV's, generally expressed as 8-hour time-weighted average exposure limits, are based upon industrial studies, human and animal chamber studies, and combinations of all three, as described in associated criteria documentation [5]. Table 8-2 present examples for selected pollutants of particular concern in the indoor residential environment.

8.2.3 Occupational Safety and Health Administration (OSHA)

When OSHA was formed in April 1971 subsequent to the Occupational Safety and Health Act of 1970, it set out to quickly develop and set mandatory occupational safety and health standards. To facilitate the process in regard to airborne contaminant exposure limits, OSHA practically without exception promulgated the ACGIH list of TLV's existing in 1970 by publishing them in the Federal Register of May 29, 1971. Simultaneously, it incorporated the American National Standards for 18 contaminants into law. These were published by the American National Standards Institute (ANSI) under their Z37 series of standards [7]. Consequently, it is not surprising that current OSHA Permissible Exposure Limits (PEL's) for airborne contaminants of interest to this investigation are quite similar to, but not completely identical with the updated limits in Table 8-2.

8.2.4 National Institute for Occupational Safety and Health (NIOSH)

The Occupational Safety and Health Act of 1970 provided for a greatly accelerated program by NIOSH to study the health effects of exposures in the work environment, and to develop criteria for dealing with toxic materials and harmful agents, including safe levels of exposure. To meet its responsibilities, NIOSH embarked on a program to develop detailed criteria documents for individual substances and to recommend revisions to OSHA regulations where changes appeared warranted. Up to 1978, NIOSH had published criteria for almost 100 individual sub-

TABLE 8-1. NATIONAL PRIMARY AND SECONDARY AMBIENT AIR QUALITY STANDARDS

Pollutant	Type of Standard	Averaging Time	Frequency Parameter	Concentration µg/m³	ppm
Carbon monoxide	Primary and secondary	1 hr 8 hr	Annual maximum[a] Annual maximum	40,000 10,000	35 9
Hydrocarbons (nonmethane)	Primary and secondary	3 hr (6 to 9 a.m.)	Annual maximum	160[b]	0.24[b]
Nitrogen dioxide	Primary and secondary	1 yr	Arithmetic mean	100	0.05
Photochemical oxidants[c]	Primary and secondary	1 hr	Annual maximum	160	0.08
Particulate matter	Primary	24 hr 24 hr	Annual maximum Annual geometric mean	260 75	- -
	Secondary	24 hr 24 hr	Annual maximum Annual geometric mean	150 60[d]	- -
Sulfur dioxide	Primary	24 hr 1 yr	Annual maximum Arithmetic mean	365 80	0.14 0.03
	Secondary	3 hr	Annual maximum	1,300	0.5
Lead	Primary	90 day		1.5	
Ozone	Primary and Secondary	1 hr		235	0.12

[a]Not to be exceeded more than once per year.

[b]As a guide in devising implementation plans for achieving oxidant standards.

[c]Expressed as ozone by the Federal Reference Method.

[d]As a guide to be used in assessing implementation plans for achieving the annual maximum 24-hour standard.

Source: Reference 4.

TABLE 8-2. SELECTED ACGIH THRESHOLD LIMIT VALUES (TLV'S)

Contaminant	TLV ppm	TLV mg/m^3*
Carbon dioxide	5,000	9,000
Carbon monoxide	50	55
Formaldehyde	2	3
Nitric oxide	25	30 (ceiling
Nitrogen dioxide**	5	9 "
Nuisance particulates		10-total dust (<1% quartz) 5-respirable fraction
Ozone	0.1	0.2
Sulfur dioxide***	2	5

*8-hour time-weighted average exposure limits.

**A change to 3 ppm (6 mg/m^3) has been proposed.

***TLV was 5 ppm (13 mg/m^3) prior to 1980.

Source: Reference 6.

stances or chemical families. Selected recommendations are presented in Table 8-3 for indoor air contaminants addressed by OSHA or NIOSH.

8.2.5. American Society of Heating, Refrigeration, and Air-Conditioning Engineers (ASHRAE)

Standards developed by ASHRAE have had widespread impact on internal building environments due to their incorporation by reference into numerous building codes. Those of particular interest include Standards 62-73 and 90-75.

Standard 62-73, entitled "Standard for Natural and Mechanical Ventilation" was published in 1973 after nine drafts and an extensive review process starting in 1966. As noted by McFadden et al. [1], the particular wording of the standard is somewhat ambiguous in describing the applicability of numerical standards for air quality, but appears to suggest that the limits given in Table 8-4 apply indoors. Also noted is the ASHRAE stipulation that "...air shall be considered unacceptable for ventilation use in accordance with this standard if it contains any contaminant in a concentration greater than one-tenth the TLV currently accepted by the ACGIH."

ASHRAE Standard 90-75, entitled "Energy Conservation in New Building Design" was published in 1975 with the objective of promoting energy conservation through appropriate selection and design of buildings and their systems. Section 5.0 of the standard requires that air utilized for ventilation conform to ASHRAE Standard 62-73, but also suggests a set of "minimum" ventilation rates rather than the set of higher "recommended" rates also presented. This requirement subsequently led to air quality problems in some new buildings, thus prompting ASHRAE to initiate revision of Standard 62-73 by appointing a Standards Project Committee in July of 1978.

The draft of the revised standard was made available for public comment from May 1 to June 30, 1980 with the new title of "Standards for Ventilation Required for Minimum Acceptable Indoor Air Quality." It specified acceptable contaminant levels in outdoor air used for ventilation by more precisely specifying previous criteria, set forth maximum permissible indoor concentrations in terms of one tenth the OSHA standard for a given pollutant, and defined acceptable air quality as "ambient air in which there are no known contaminants at harmful concentrations and with which a substantial majority (usually 80%) of the people exposed do not express dissatisfaction." Primary ventilation criteria were recommended separately for smoking and non-smoking areas such that rates for non-smoking areas were generally <u>less</u> than the "minimum" rates previously suggested and rates for smoking areas were <u>equal</u> to or <u>greater</u> than previous "minimum" rates.

TABLE 8-3. SELECTED NIOSH RECOMMENDATIONS

Contaminant	NIOSH Recommended Standard
Carbon dioxide	10,000 ppm as 10-hr TWA* 30,000 ppm as 10 min ceiling
Carbon monoxide	35 ppm as 10-hr TWA 200 ppm as ceiling
Formaldehyde	0.8 ppm as 30-min ceiling
Nitric oxide	25 ppm as 8-hr TWA
Nitrogen dioxide	1 ppm as ceiling
Ozone	Not considered
Sulfur dioxide	0.5 ppm as 8-hr TWA

*TWA = time-weighted average.

Source: Reference 8.

TABLE 8-4. MAXIMUM ALLOWABLE CONTAMINANT CONCENTRATIONS FOR VENTILATION AIR (From ASHRAE Standard 62-73)

Contaminant	Annual Average (Arithmetic Mean) μg/m^3	Short-Term Level (Not to be exceeded more than once a Year) μg/m^3	Averaging Period (hr)
Particulates	60*	150*	24
Sulfur Oxides	80	400	24
Carbon Monoxide	20,000	30,000	8
Photochemical Oxidant	100	500	1
Hydrocarbons (not including methane)	1,800	4,000	3
Nitrogen Oxides	200	500	24
Odor		Essentially Unobjectionable**	

*Federal criteria for U.S. by 1975.
**Judged unobjectionable by 60% of 10 untrained subjects.

A potential problem with the revised standard stems from the observation that specified ventilation rates are solely a function of whether smoking is permitted and do not fully consider the possible presence of other common sources of indoor air pollution. Although numerical limits are denoted for concentrations of toxic substances, as was the case with the prior version of 62-73, one must reflect on whether building designers will simply follow the ventilation rate suggestions in most cases rather than expending the time and resources necessary to properly obtain and utilize air quality information. Indeed, one must also wonder if the current state-of-the-art permits a comprehensive assessment of potential indoor air quality problems in terms of the radon and formaldehyde sources that might be present in a new building.

8.2.6. Other Organizations

U.S. Navy publication NAVSEA 0938-011-4010 provides air quality criteria for contaminants in the air of nuclear submarines. Limits represent "the best available information regarding the maximum concentrations to which personnel may be exposed without adverse effects." Table 8-5 presents selected criteria of interest.

The Commonwealth of Pennsylvania Department of Health publishes [9] a list of short-term limits as part of its "Regulations Establishing Threshold Limit Values in Places of Employment." These are upper limits of exposure for which a workman may be exposed for a specified short period of time [2].

A list of emergency exposure limits is published [10] by the Committee on Toxicology of the National Research Council, an operating arm of the National Academy of Sciences and National Academy of Engineering. These limits provide guidance in advance planning for emergencies [2].

An extensive list of chemicals is covered in the Hygienic Guide Series [11] published by the American Industrial Hygiene Association. Information provided for occupational exposures includes 8-hour time-weighted average limits, short exposure tolerance data, and atmospheric concentrations immediately hazardous to life [2].

As noted above, the American National Standards Institute (ANSI) publishes workplace air quality standards [7]. Eight-hour time-weighted average limits are essentially the same as those provided by the ACGIH. Also provided are "acceptable ceiling concentrations" and "maximum acceptable peak concentrations."

The only nonworkplace indoor air quality standard for the United States discovered by McFadden et al. [1] was one for ozone promulgated by the Food and Drug Administration. Section 801.415 of Title 21 of the Code of Federal Regulations effectively prohibits

TABLE 8-5. CONTAMINANT LIMITS* FOR NUCLEAR SUBMARINES

Contaminants	90-Day Limit	24-Hour Limit	1-Hour Emergency Limit
Carbon dioxide**	0.8%	1%	2.5%
Carbon monoxide	15	200	200
Formaldehyde	0.5	1	3
Hydrocarbons			
(a) Total Aromatics (Less Benzene)	10 mg/m^3	***	***
(b) Total Aliphatics (Less Methane)	60 mg/m^3	***	***
Nitrogen dioxide	0.5	1.0	10
Ozone	0.02	0.0	1
Sulfur dioxide	1	5	10

*Limits are in ppm unless otherwise specified.

**90-day limit is an average. Levels not to exceed a maximum of 1%, tactical situation permitting. 90-day limit for Trident and later class submarines is 0.5% maximum.

***Limit has not been established.

Source: U.S. Navy Publication NAVSEA 0938-011-4010.

the sale of any device that would cause an ozone concentration in excess of 0.05 ppm "in the atmosphere of enclosed space intended to be occupied by people for extended periods of time, e.g., houses, apartments, and offices. This applies to any such device, whether portable or permanent or part of any system, which generates ozone by design or as an inadvertant or incidental product."

8.3 STANDARDS AND CRITERIA OF FOREIGN/INTERNATIONAL REGULATORY AGENCIES AND ORGANIZATIONS

Information related to standards and criteria of foreign/international regulatory agencies and organizations was collected from published sources and through communication with diplomatic and technical personnel. Correspondence which, in most cases, provided little additional information, was received from Australia, Austria, Belgium, Denmark, England, France, Greece, Holland, Iceland, India, Ireland, Israel, Italy, Japan, Mexico, New Zealand, Norway, South Africa, Sweden, Switzerland, and West Germany.

8.3.1 Occupational Exposure Standards

8.3.1.1 West Germany

Maximum allowable concentrations for occupational exposures in West Germany are developed by a commission of the German Research Association and adopted by the Ministry of Labor and Welfare. Although some variations are apparent, the values in essence reflect those set forth by the ACGIH [2].

8.3.1.2 United Kingdom

The Department of Employment of the United Kingdom utilizes a list of occupational exposure limits as "benchmarks" for the inspectorate of its Factory Inspection Service. These also are essentially the values set forth by the ACGIH [2].

8.3.1.3 France

French legal codes pertaining to worker protection provide numerical exposure limits for very few specific substances. The rationale for this stems from an understanding that such limits are not inflexible, absolute dividing lines between safety and hazard [2].

8.3.1.4 U.S.S.R.

The Soviets select maximum acceptable concentrations for occupational exposures on the basis of minimal reactions of the higher nervous system and physiological alteration. Since minimal changes are considered to denote the borderline between safety and hazard, and since a safety factor is subsequently applied, Soviet standards are usually lower than those of the United States [2]. Table 8-6 summarizes known limits for selected contaminants of concern, and provides selected Czechoslovakian exposure limits for comparison purposes.

TABLE 8-6. SELECTED OCCUPATIONAL EXPOSURE LIMITS OF THE USSR AND CZECHOSLOVAKIA

Contaminant	Country	Exposure Limit (ppm)
Carbon dioxide	Czech.	5,000
Carbon monoxide	USSR	18
	Czech.	30
Formaldehyde	USSR	0.8
	Czech.	1.6
Nitrogen dioxide	USSR	2.0
Sulfur dioxide	USSR	4.0
	Czech.	4.0

Source: Reference 5.

8.3.1.5 Eastern Bloc Nations

Ministries of Health in Eastern bloc nations usually promulgate occupational exposure standards in terms of specific numerical values. With the exception of Bulgaria, most countries do not adopt values identical with those in the U.S.S.R. [2], as is evident from inspection of Table 8-6.

8.3.1.6 Asiatic Nations

Several asiatic nations have workplace air quality standards. The most notable of these are Japanese which are largely based on exposure limits given by the ACGIH [2].

8.3.2 Ambient Air Quality Standards

In the occupational health area, it is apparent that most nations of the free world base specific numerical standards, if they have them, on the recommendations of the ACGIH. The Soviet Union, due to its rather unique "philosophy" in setting standards, generally establishes lower limits for exposures, but other nations of the Eastern bloc do not necessarily follow its lead. The situation in terms of ambient air quality standards is somewhat similar, but there is considerably less uniformity.

Table 8-7 presents the standards either promulgated or recommended in a number of countries together with recommendations of the World Health Organizations [12]. The table was pieced together from a variety of sources, some of which were clearly of dubious accuracy with little regard for whether specified measurement methods were similar or whether the numerical values were to be interpreted as averages for the indicated time durations or as maxima. Nevertheless, the comparison is valuable in that it illustrates major differences in the contaminant concentrations selected by various nations for air quality criteria. While the lack of international agreement on air quality standards could be due, to a minor degree, to racial differences in susceptibility, it primarily reflects the lack of understanding of the dose-response relationship at low levels and varying governmental policies for prescribing margins of safety.

8.3.3 Indoor Air Quality Standards

McFadden et al. [1] surveyed environmental officials in some 50 countries to determine whether indoor air quality standards were in use. Responses from Australia, Denmark, France, Hong Kong, Israel, Japan, Mexico, Poland, Singapore, South Africa, Sweden, Yugoslavia, and several Canadian Provinces indicated that such standards do not exist and have not been proposed for nonworkplace air. Many, however, noted the development of standards for outdoor ambient air quality and/or for occupational exposures, and commented that these would be applicable.

COUNTRY	SO_2 24-hr (μg/m³)	CO 8-hr (ppm)	CO 0.5-1 hr (ppm)	NO_2 24-hr (μg/m³)	NO_2 0.5-1 hr (μg/m³)	PARTICULATE MATTER 24-hr (μg/m³)	OXIDANTS 0.5-1 hr (ppm)
USSR	50		2.7	85	85	150	
POLAND (Specially Protected)	75		2.7			75	
JAPAN	130	20		80-110		100	0.06
CSSR	150		5	100	300	150	
CANADA	180	5	13	190	380	120	0.05
FINLAND	250	9	35	200	560	150	
SWEDEN	250						
ROMANIA	250		5.2	100	300	150	0.005
ISRAEL	250	10	30	600	1000	200	0.20
ONTARIO	260					90	
USA (Secondary)	260	9	35			150	0.08
HOLLAND	275						
TURKEY	300						
POLAND (Protected)	350					200	
USA (Primary)	365	9	35		470-940*	260	0.08
W. GERMANY	400		35		280	200	
SWITZERLAND	500-750						
WORLD HEALTH ORGANIZATION		9*	35*		190-320*		0.06*

*Recommended. Note that the U.S. short-term NO_2 recommendation is highly controversial.

Source: References 4, 12, 13, 14, 15, 16, and 20.

TABLE 8-7. SELECTED AMBIENT AIR QUALITY STANDARDS

Exceptions to the above statements include a maximum allowable indoor air quality standard of 0.04 mg/m^3 adopted by Sweden for formaldehyde, a formaldehyde emissions standard developed in Denmark, and an ozone emissions standard published by the Canadian Standards Association. In addition, there are indications in the literature that Japan has building environment codes that provide concentration limits for toxic substances [1].

8.4 JURISDICTIONAL ASPECTS

Since the indoor residential air quality problem has only recently been recognized, it is not surprising to find that its resolution is not a specifically designated responsibility of any particular Federal agency. Nevertheless, it is apparent that various agencies, and their counterparts at the state and local levels, have indirect authority to study the problem and to propose and/or require remedial actions. More specifically, it is seen that:

- The Consumer Product Safety Commission has the responsibility to protect the public from consumer product risk or injury [18]. It is not unreasonable to consider that the commission has the authority to regulate the sale and characteristics of building materials or appliances that may under certain circumstances pose a health risk to the public.

- The Department of Housing and Urban Development (HUD) is responsible for programs concerned with housing needs and developing and improving the Nation's communities. HUD has promulgated Minimum Property Standards for all newly developed Federally-assisted housing and has the ability to attach conditions to the acceptance of assistance under a wide variety of housing programs [19]. In the future, these standards or conditions may incorporate indoor air quality criteria.

- The Veterans Administration (VA) and the Farmers Home Administration (FmHA) to a large extent utilize HUD's Minimum Property Standards in setting conditions on the granting of housing assistance, as does the Government National Mortgage Corporation [19]. Consequently, it is likely that HUD has the authority to impact housing characteristics on a widespread basis.

- The Department of Energy (DOE) has the responsibility to develop and encourage state adoption of building codes designed to conserve energy [19]. It is studying the impact of energy conservation measures on indoor air quality and may ultimately propose modifications to building codes, modifications likely to be adopted by many states.

- The Department of Defense owns and operates 385,000 units of family housing within the continental United States [19]. It clearly has the authority to modify characteristics of this housing or to impose requirements on new housing projects under its control.

- A review of various legislation [18] suggests that the Environmental Protection Agency (EPA) does not have the explicitly defined responsibility to regulate indoor air quality. Nevertheless, it is studying the problem and formulating recommendations to other agencies in an advisory role.

- State and local authorities have the responsibility to develop and enforce building codes. Since ASHRAE standards cited previously have been adopted on a widespread basis by the states, they also have the authority to regulate indoor qir quality.

8.5 APPLICABILITY OF STANDARDS

The occupational exposure limits promulgated or recommended by OSHA, NIOSH, the ACGIH, and others are intended to represent conditions under which nearly all workers may be repeatedly exposed on a day after day basis without suffering adverse effects. With few exceptions, the limits incorporate safety margins and have generally been successful in maintaining worker health. It is reasonable, therefore, to ask why such limits are in some cases more than an order of magnitude higher than ambient air quality standards, and to initiate a debate on which set of standards might be applicable for the indoor residential environment. Part of the answer lies in the difference in populations addressed, while another concerns the methods utilized to develop the standards.

Occupational exposure limits are usually based in part on observations of workers in the industrial environment and are generally expressed as 8-hour or so time-weighted exposures for a 40-hour work week. There are inherent assumptions that: 1) there is a 16-hour or so time period between successive exposures; and 2) the workers are healthy individuals with no special sensitivity to the contaminants being addressed.

Ambient air quality criteria are intended to protect not only healthy and insensitive members of the population, but also possibly sensitive subpopulations of the very young, the elderly, and the infirm. Additionally, they are intended to protect these individuals from the effects of continuous exposures not interrupted by substantial "recovery" periods. Thus, such standards, in attempting to protect all elements of society, are intentionally and necessarily conservative for healthy individuals capable of joining the industrial work force. One can therefore conclude that:

- Healthy individuals intermittently and relatively infrequently exposed to contaminant concentrations at levels at or below occupational exposure limits are unlikely to be adversely impacted.

- It is not known at present whether occupational exposure limits are suitable for continuous exposures of healthy individuals. There is a likelihood they are not.

- There is cause to conclude that occupational exposure limits <u>may</u> not be appropriate for application to the continuous or intermittent exposures of particularly sensitive subpopulations of society.

McFadden et al. [1] note that another reason for the discrepancy between occupational and ambient air quality standards lies in the criteria used in the development of each standard. Occupational limits are more likely to be based on the specific effects of a toxic agent acting alone, as determined from animal or chamber studies or observations of workers. The ambient air quality limits are frequently based on epidemiological studies where populations were exposed to concentrations of contaminants during air pollution episodes and experienced increased mortality or morbidity. Standards are often downward extrapolations of such data.

One problem being increasingly recognized is that one basis for epidemiological study findings, i.e., the contaminant <u>concentrations</u> measured in the outdoor air, may not have been representative of the <u>exposures</u> of sensitive individuals adversely impacted by the air pollution episodes considered. Since these subpopulations are likely to have spent a considerable amount of time indoors, and since indoor exposures may have been greater than those outdoors, it is entirely feasible to hypothesize that the relationship between contaminant concentrations in the outdoor air and the extent of increased mortality or morbidity may not have been correctly defined in the absolute sense. In other words, it may ultimately be found that a level of X ppm in air previously associated with a given level of injury should have been adjusted to a level of 2X or so due to increased exposures in enclosed and poorly ventilated environments for the individuals that were adversely impacted. Thus, ambient air quality standards might be applicable to the outdoor air only, and not also to indoor environments.

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APPENDIX I

INDOOR AIR QUALITY

ANNOTATED BIBLIOGRAPHY OF SELECTED STUDIES

AUTHOR: Belles, F. E., R. L. Himmel, D. W. Dewerth

TITLE: Measurement and Reduction of NO_x Emissions from Natural Gas-Fired Applications

SOURCE: American Gas Association Laboratories; Presented at Air Pollution Control Association Conference, Boston; June 15-20, 1975

POLLUTANTS EXAMINED: Carbon monoxide (CO), Oxides of nitrogen (NO, NO_2)

SUBJECT: This paper updates A.G.A. laboratory work on emission measurements from natural gas-fired appliances such as water-heaters, room heaters, boilers and their pilot lights. In addition, it provides data on factors which affect appliance emission levels (operating time, fuel, input, aging, etc.) and discusses a prototype range top that reduces NO_x emissions.

METHODOLOGY:

- Air Sampling Technique/Analytical Chemistry - All samples were taken downstream from a drafthood using a dispersive infrared spectrophotometer.
- Statistical Analysis - Air concentrations of CO, NO, and NO_2 (ppm) are presented as mean values with standard deviations. NO_x emission factors (lbs/10^6 BTU) are also presented. Graphs provide concentrations due to operation of appliances (water heaters, room heaters) as a function of operational characteristics. No tests for statistical significance were performed.

RESULTS: Refer to the text for detailed review of the data on individual appliances. Some representative results for performance factors that affected appliance emissions were a reduced fuel input rate caused a reduction in NO and NO_x; when air movement around the room heater was controlled, the relative standard deviation of the NO_x emission levels was reduced by a factor of the ten. NO_x reduction techniques involved increases in primary aeration and placement of a re-radiating screen on the burner. This reduced the flue temperature and decreased NO_x emissions by 55%.

COMMENT: This study is an in-depth analysis of emissions from gas appliances and available techniques to control these emissions at the source. Nevertheless, application of these experimental laboratory results to predict exposures of home inhabitants who use these appliances under a wide variety of operating conditions is not necessarily warranted. The data do provide an estimate of emissions and their variability.

AUTHOR: Biersteker, K., H. DeGraaf, A. G. Nass

TITLE: Indoor Air Pollution in Rotterdam Homes

SOURCE: International Journal of Air and Water Pollution, Vol. 9:343-350 (1965)

POLLUTANTS EXAMINED: Smoke and Sulfur dioxide (SO_2)

METHODOLOGY:

- Study Design - Sixty-five homes were chosen by the Rotterdam Housing Department as representative of homes in that city. Three parameters: year of construction, type of heating system, and smoking habits of inhabitants were compared to smoke and SO_2 levels to identify possible independent relationships. The primary objective of the study, however, was to determine how outdoor pollutant levels affected indoor levels.
- Air Sampling Technique/Analytical Chemistry - Continuous 24-hour area sampling for smoke and SO_2 was performed simultaneously indoors (living room) and outdoors. The sampling train consisted of a glass fiber filter to trap smoke (analyzed by reflectometer) and a Drechsel bottle containing a solution of hydrogen peroxide in water. The SO_2 was analyzed by titration of total acidity, this being an outdated analytical technique that at best could only provide a qualitative representation of SO_2 levels. It is significant that sampling of indoor pollutants was restricted to one location.
- Statistical Analysis - Indoor smoke and SO_2 levels were shown as percentages of outdoor levels (individual mean indoor and outdoor values for homes were also shown). These percentages were then used in multiple regression analyses to identify possible relationships between year of construction, heating methods, and smoking habits.

RESULTS: Smoking habits of inhabitants were shown to have a significant ($p< 0.001$) independent effect on indoor smoke concentrations. A significant ($p < 0.05$ negative correlation (-0.33) was shown between year of construction (1919 - 1960) and indoor SO_2 levels. The authors loosely related elevated SO_2 levels with faulty heating systems, but the lack of specificity for indoor sources and the qualitative nature of teh SO_2 measurements makes any association difficult.

In their final discussion, the authors compare their outdoor SO_2 and smoke levels for one day (at an unstated location in Rotterdam) to a 1962 Rotterdam daily mortality study for residents over 60 years old. It is difficult to draw any conclusions from this comparison because the lack of correlation between pollution levels and exposures in the studied populations.

AUTHORS: Cote, W.A., W.A. Wade, J.E. Yocum

TITLE: A Study of Indoor Air Quality

SOURCE: U.S. Environmental Protection Agency, Office of Research and Development Contract No. 68-02-0745, Washington, D.C. September 1974

POLLUTANTS EXAMINED: Oxides of Nitrogen (NO and NO_2) and Carbon monoxide

METHODOLOGY:

- Study Design - Three separate tasks were executed in this study; 1) A laboratory study to measure NO, NO_2, and CO emissions from gas appliances (with/without ventilating hoods, various burner types and ages, etc.) under different operating variables including air-fuel ratios, flame intensity, time and temperature, and use of pilot lights. 2) Field studies collecting measurements for NO_2, NO and CO made continuously over 2-week periods in 4 homes with gas stoves. 3) An inventory of indoor pollutant sources which involved a survey to develop use patterns of aerosol products and to estimate the effect of such use on indoor air quality. This latter task was based on a survey of TRC employee's habits and no field measurements were performed. The predominant portion of the study deals with the second task and includes an analysis of the large amount of data generated from the four houses. These residences represented wide differences in land use, location with relation to large point sources, house type and layout, gas appliance age and life styles (single adults to large familites). These variables are well-summarized in the study. One potentially useful piece of information not provided was the ventilation rates (air changes per hour) in individual residences. In one residence time decay rates of the pollutants were studied to evaluate secondary pollutant reactions.

  One disadvantage of this study design, intensive data collection on a small sample, is the effect of lost data on the significance of the outcome. Approximately fifty percent of the two-hour averages were lost because of equipment malfunction, etc. This loss of data limits the application of the study beyond the houses which were studied.

- Air Sampling Technique - The TRC integrated sampling method was used for laboratory evaluation of the pollutant emission levels for gas appliances and the field studies. Detailed explanations of the method and sampling locations are provided in the text. One additional test which would have helped in evaluating the laboratory emission levels would have been to vary the laboratory air exchange rate to check the effect on steady state conditions. Because the exchange rate was high (60 ACPH), these data may not represent normal residential conditions. Application of the three, five-minute periods per hour of NO, NO_2 and CO in the field study eliminated close study of peak concentrations. Locations of the sampling points does give a gradient of pollutant levels through the house, but it is difficult to relate the gradient to continuous personal exposures for the inhabitants.

- Analytical Chemistry - Both the chemiluminescent method for NO/NO_2 and the NDIR method for CO were utilized. Calibration techniques were well characterized in the study. Unfortunately, periodic equipment malfunction resulted in some data loss.

- Statistical Analysis - The field data was "smoothed out" over twelve two-hour arithmetic means for the day. Then, daily means were computed from the two-hour means and, finally, a composite day representing daily means for six days was computed for NO_2 levels. No variance or standard deviations were calculated and two-hour averages were calculated based on 3, 4, 5, or 6 five-minute periods.

<u>RESULTS</u>:

TASK 1 - Emission levels - As expected, there were significant emission levels from the gas stoves for the three pollutants (NO-200-1000 mg/hr, NO_2 100-500 mg/hr, CO-1000-4000 mg/hr). Differences in emission levels were observed for older and newer stoves, but these are not directly attributable to age or design differences. Amounts of pollutants generated were related (by observation, not statistical test) to the number of burners in operation and the amount of gas being consumed. Vented stove hoods were moderately effective in removing gaseous pollutants but recirculating fans were not effective. The charcoal filter was reported to have a 0% removal efficiency.

TASK 2 - Field Measurements - Stove use and outdoor air quality both influence indoor air quality. This joint influence is a function of house permeability as determined by season. In several cases, levels of indoor NO_2 and CO could exceed the air quality standards for these pollutants if such outdoor standards were to be applied indoors. The half-life of indoor CO was 2.1 hour, NO, 1.8 hours, and NO_2 was .6 hours in one residence. There was significant infiltration of outdoor air which affected indoor air quality.

TASK 3 - Inventory of Indoor Sources - Propellant-dispersed aerosols also have a significant but widely variable impact on indoor air quality. While concentrations of propellants are estimated to be below the TLV for these materials, special circumstances may cause these levels to be exceeded.

<u>COMMENTS:</u>

Any comparison of the field data (Task 2) to standards must be made with caution. For example, the highest indoor values for CO, measured in the winter right above the stove, from the eight-hour period from 12 noon to 8:00 p.m., give a net mean (indoor minus outdoor) of 10,000 $\mu g/m^3$. Since only 23 minutes of the 480-minute period were measured (3-5-minute samples/hour) the concentration assumes steady-state conditions with little peak activity. This sampling technique is an excellent survey tool, but continuous area sampling is preferable for measuring highly variable indoor air quality levels.

The final task was based on a hypothetical model assuming the worst possible exposure conditions over an eight-hour period. Various population sampling methods for aerosol usage and further assumptions on half-lives of propellants, or use in airtight spaces could be representative of exposures, but field-sampling is necessary. Two important aspects of the propellant use problem which need to be investigated are short-term exposures or peak concentrations in the breathing zone and the interaction of these low levels of aerosols from propellants with other indoor pollutants.

AUTHORS: Derham, R.L., G. Peterson, R.H. Sabersky, F.H. Shair

TITLE: On the Relation Between the Indoor and Outdoor Concentration of Nitrogen Oxide

SOURCE: Journal of Air Pollution Control Association, Vol. 24(2) pp. 158-161, February (1974)

POLLUTANT EXAMINED: Nitrous oxides (NO, NO_2), Carbon monoxide (CO) and Ozone (O_3)

METHODOLOGY:

- Study Design - Simultaneous measurements of NO, NO_x CO and O_3 were taken on the inside and outside of a building in the Los Angeles basin area for a period of one month. The study was conducted at a time of the year when high levels of these pollutants would be expected in this area. The focus of the study was to quantify the relation between indoor and outdoor concentrations of these pollutants. A secondary objective was to measure ozone inside the building and evaluate its impact on indoor NO_2 reaction levels.
- Air Sampling Technique/Analytical Chemistry - NO and NO_x measurements (NO_2 obtained by difference) were made using chemiluminescent NO/NO_x gas analyzers (± 0.01 ppm). CO measurements were made using an infrared CO analyzer and ESI Ecolyzer (both read to 0.5 ppm). Ozone was analyzed in the first experiment by UV absorption (Dasabi ozone meter ± 0.01 ppm). Outdoor samples were taken next to the ventilation intake duct on the roof of the building and indoor measurements were in a room with 12 air changes per hour with a forced ventilation system operating and 1 air change per hour with the system off. In the second experiment, two NO/NO_x analyzers were placed in a room, one measuring NO and the other NO_x; the difference was assumed to be NO_2. Uniformity of the indoor atmosphere was measured with balloon samples throughout the building. CO sampling at the intake was continuous.
- Statistical Analysis - Continuous 24-hour readouts are presented with pollutant level concentrations (ppm) vs. time.

RESULTS: The results indicate that there is a direct relationship between indoor and outdoor NO and CO concentrations (particularly during rush hour traffic) and that the phase lag between the concentrations depends principally on the ratio of the building volume to the ventilation rate. The authors suggested reducing building ventilation rates during outdoor pollution peaks to reduce indoor levels. In the second experiment, it was seen that NO and O_3 were not found simultaneously indoors, so it was concluded that indoor NO_2 production was low. The authors were careful to point out that these conclusions were based on general observations of the data. The daily variations in pollutant levels were seen to be strongly dependent on traffic and meteorological conditions, with no definite patterns being evident.

COMMENT: This study was limited to characterization of indoor levels as a function of outdoor levels and ventilation rates. No attention was given to the influence of building infiltration rates or indoor pollutant sources. The sampling methodology and analytical chemistry were quite good. The authors qualitatively characterized indoor/outdoor NO, NO_2, CO and O_3 levels and their high degree of variability.

AUTHOR: DeWerth, D.W.

TITLE: Pollutant Emissions form Domestic Gas-fired Appliances

SOURCE: Journal of the Air Pollution Control Assoc. 24 (2); 156-161, Feb. 1974.

POLLUTANT EXAMINED: Carbon monoxide (CO), Nitric oxide (NO), Nitrogen dioxide (NO_2).

SUBJECT: Emission levels from range tops and furnace burners were studied when flames were adjusted and NO_x control techniques applied.

RESULTS: The first section of this report deals with modifications to gas range designs that reduce CO and NO_x emissions. Forty to fifty percent reductions in NO_x emission levels (lbs/10^6 BTU) were achieved by modifying burner cup design, secondary airflow, primary air injection, and by providing wire mesh screening mounted at flame heights. Similar adjustments were made to 34 forced-air furnace burners in the field. Measurements taken on the furnace burner in poor adjustment (i.e., with a flame) indicate a wide variation in CO levels ($\bar{x}$ = 359 S.D. = 321 ppm), as well as NO_x emission factors of 0.104 - 0.074 lbs/10^6 BTU for multiport and single port burners.

COMMENTS: The emission data presented are the result of laboratory experiments or tightly controlled field measurements. Consequently, their usefulness for efforts to predict indoor air pollution exposures is limited. The report is most useful in its evaluation of engineering/design control methods to reduce emissions at the source.

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AUTHORS: Goldstein, B.D.; Melia, R.W.; Chinn, S.; Florey, C.V.; Clark, D; and John, H.H.

TITLE: The Relation Between Respiratory Illness in Primary School Children and the Use of Gas Cooking. II-Factors Affecting Nitrogen Dioxide Levels in the Home.

SOURCE: International Journal of Epidemiology, Vol. 8(4). pp. 339-345. 1979.

POLLUTANT EXAMINED: Nitrogen dioxide (NO_2)

METHODOLOGY: Study Design - A sample of 516 homes in a 4 Km^2 area was used to determine kitchen NO_2 levels. A randomly chosen group of homes (25%) were sampled in the bedroom, also. In addition to NO_2 sampling, information about the gas stove (pilot lights, open grills, oven), about kitchen ventilation (open/closed window), gas furnaces for heating, number of inhabitants, and smokers were gathered by questionnaire. A follow-up inspection to measure kitchen area and details on gas cookers was conducted in fifty-eight homes. Indoor and outdoor sampling was conducted for one week. Infiltration rates and meteorological conditions werenot measured. No mention was made of maintenance condition of the appliances or the presence of outdoor NO_2 sources.

Air Sampling/Analytical Chemistry - The authors report comparison testing with the NO_2 sampler and standard chemiluminescent NO_2 monitors which indicated an accuracy of better than $\pm$ 10%* when used in normal domestic kitchens. Outdoor NO_2 levels were not matched with individual homes, but were determined in a non-specific grid pattern covering the entire area.

RESULTS: NO_2 levels in gas kitchens ($\bar{x}$ = 112.2, S.E. = 2.7 ppb, range 5-317 ppb, n = 428) were higher than those in electric kitchens ($\bar{x}$ = 18.0, S.E. = 2.4 ppb, range 6-118 ppb, n = 87). Outdoor levels ($\bar{x}$ = 18.5, range 14-24, n = 75) were similar to those found in electric kitchens. An additive analysis of variance was performed on 420 of the gas kitchens to determine what variables from the questionnaire accounted for the range of NO_2 values. Significant positive correlations were seen with pilot light use. An interesting negative contribution to the NO_2 levels was seen with "flueless gas fires" (n = 15) which would be expected to have a major contribution to NO_2 levels. This may illustrate a weakness in the questionnaire (which may also affect the positive findings) or the existence of unreported indoor or outdoor NO_2 sources.

*A.J. Apling, K.J. Stevenson, B.D. Goldstein, R.W. Melia, and Atkins "Air Pollution in Homes - 2: Validation of diffusion tube measurements of nitrogen dioxide. Warren Spring Laboratory, Stevenage, Publ. No. LR311 (AP), 1979.

Significant relationships were found in 58 homes between high NO_2 values and total number of meals consumed and other uses of the cooker for space heating or drying clothes.

COMMENTS: This study is an improvement over previous air sampling reports due to the provision of outside sampling, the characterization of indoor sources, and the larger sample size. Unfortunately, as the authors pointed out, only about half of the high NO_2 levels observed could be properly accounted for in the analysis. Further characterization of outdoor sources, the effect of various weather conditions (wind, temperature, humidity) on the NO_2 sampler, quantification of gas consumption, and ventilation rates would all help to clarify the results. In addition, it is seen that the weekly average concentrations do not describe the spatial distribution of pollutants or their peak values. Overall, the report provides a significant amount of data on the contribution of gas appliances to indoor NO_2 levels, but further clarification of relationships is necessary.

AUTHORS: Halstead, D.J.; Munro, A.J.E.

TITLE: The Sampling, Analysis and Study of the Nitrogen Oxides Formed in Natural Gas/Air Flames

SOURCE: Proceedings of the Conference on Natural Gas Research and Technology, February 28 - March 3, 1971

POLLUTANT EXAMINED: Nitrogen oxides

SUBJECT: Emission levels of NO_x from one furnace gas burner

METHODOLOGY:

- Air Sampling and Analytical Technique - A non-dispersive infrared analyzer (NO) and the manual Griess-Saltzman methods (NO_2, NO) were selected to measure NO_x levels. Two negative effects on these sampling methods were studied in detail: 1) the effect of water vapor and drying methods on NO_2 recovery; and 2) the catalytic reduction of NO in metal probes for gas sampling. The authors strongly recommended silica or silica-lined probes for sampling. They also found that substantial NO_2 was lost using drierite, glass wool, and silica gel as drying agents.

RESULTS: Maximum NO_x emissions from the furnace burner occurred at a low level(5%) of excess air. Additional results described NO_x (ppm) levels as a function of distance from the flame and temperature.

COMMENT: This was an excellent evaluation of NO_x levels generated by a gas burner. Although chemiluminescence is the preferred method today (10 years later), a very high correlation (.97) with NDIR was demonstrated for NO by the EPA. This particular study only examined one burner, but its methodology for emission level testing has since been generally applied.

AUTHORS: Hollowell, C.D.; Budnitz, R.G.; Case, G.D.; Traynor, G.W.

TITLE: Combustion-Generated Indoor Air Pollution: I. Field Measurements, 8/75-10/75

SOURCE: Energy and Environment Division, Lawrence Berkeley Laboratory, University of California

POLLUTANTS EXAMINED: Gases: sulfur dioxide (SO_2), nitric oxide (NO), nitrogen dioxide (NO_2), ozone (O_3), carbon monoxide (CO). Total particulate: lead (Pb), zinc (Zn), Iron (Fe), cadmium (Ca), sulfur (S), organic forms of nitrogen (NH_4^+, Nx, NO_3^-).

METHODOLOGY:

- Study Design - Six houses with gas heating systems, (five with gas stoves, one with an electric stove), were chosen for field measurements of indoor and outdoor air pollutant concentrations as a function of gas cooking and heating appliance use. Only the home with the electric stove was measured during the "cool season." Cooking and heating usage on stoves was simulated. Additional objectives included the effects of flame adjustment and use of various types of cooking utensils and oven exhaust systems on indoor pollutant levels. There is no discussion or categorization of maintenance condition of stoves, heating systems, pertinent infiltration aspects of the houses, or of stove exhaust fans.

- Air Sampling/Analytical Chemistry - Indoor (kitchen and bedroom) and outdoor area sampling was performed for SO_2, NO, NO_2, O_3, and CO. Although it is assumed that these measurements are representative of continuous 24-hour samples, it is not clear from the text how the "measurement system" functioned. Sampling duration (days, weeks) and location of outdoor samples also were not specified. As is characteristic of most indoor air pollution studies, it is difficult to relate the indoor kitchen sample to personal exposure.

  Instrumentation for measurement of these gaseous pollutants was listed, but no calibration data for control of the precision and accuracy of the measurements was provided. This is especially important in the case of SO_2 where sensitivity of instrumentation for low SO_2 levels is difficult to achieve without interference. Information on metereological conditions (wind, temperature, humidity) was not presented. A small amount of particulate sampling was performed for elemental analysis and identification of sulfates and organic species of nitrogen.

- Statistical Analysis - Gas emission data were reported as "observed" mean values (± 15%).

RESULTS: There were observed differences between outdoor levels of CO, NO, and NO_2, and kitchen mean values of these pollutants during cooking only and use of pilot light only. These values were tabulated as mean values for five homes with the gas stove in use and gas heating off. It is difficult to determine sampling duration and variation between the pollutant levels between each home from the table. The authors compare these results to the Japanese 24-hour NO_2 standard and the one-hour CO standard for the U.S.

Additional interesting observations were: the high variability of gaseous pollutant levels from gas stoves during burner adjustment and utensil use (increased CO and decreased NO). In one home, a 40% reduction in Kitchen NO_2 levels was observed during use of a recirculating fan with the gas oven on. A slightly elevated O_3 level was seen in one home during electric stove use. Finally, elevated SO_2 levels were found in the 5 homes with gas stoves as compared to the one home with the electric stove.

COMMENTS: Although additional information is necessary to adequately assess the sampling methodology and analytical techniques, this appears to be a good initial characterization of indoor air pollutants. Lawrence Berkeley Laboratory is one of the foci for indoor air quality research. Readers should refer to their more recent publications as well as their current research program.

AUTHOR: Hollowell, C.D. and Traynor, G.W.

TITLE: Combustion-Generated Indoor Air Pollution

SOURCE: Lawrence Berkeley Laboratory, University of California/ Berkeley, 1978

POLLUTANTS EXAMINED: NO, NO_2, CO, O_3, CO_2, TSP, and RSP

RESULTS: This article is a review of previous work and includes laboratory results from LBL's experimental chamber investigating gas stove emissions. No information was given on experimental and chamber design or air sampling techniques. Results are shown as continuous levels of CO, NO, No_2 (for two hours) as a function of air exchange rates (.25-7.0 acph) with the gas oven on for one hour. As expected, high initial levels of CO, NO_2 were demonstrated when the oven was in use. The one-hour NAAQS for CO was exceeded in the first hour at .24 acph and the "recommended" one-hour NO_2 standard was exceeded at 2.5 acph.

COMMENTS: It is difficult to extrapolate these limited laboratory results to residential kitchen/household NO_2 and CO levels, but these results do add to the data base on short-term gas stove emission levels and the effect of ventilation rates on them. Further field work is necessary to validate these trends under actual conditions.

AUTHORS: Hollowell, C.D.; Berk, J.V.; Traynor, G.W.

TITLE: Impact of Reduced Infiltration and Ventilation on Indoor Air Quality in Residential Building

SOURCE: Lawrence Berkeley Laboratory - University of California, Berkeley, 1979

POLLUTANTS EXAMINED: NO_2, Formaldehyde, Radon

RESULTS: This paper provides a review of current knowledge on indoor levels of the above pollutants. Of particular interest is additional information on LBL's laboratory gas stove emission study. Chamber NO_2 levels are shown as a function of increasing ventilation rates, and the impact of a stove hood vent with fan at ASHRAE-recommended ventilation levels is demonstrated. As the hood exhaust rate is increased (50-140 cfm) the NO_2 levels decreased (0.4-0.1 ppm). The authors point out that levels of NO_2 with the gas oven on for one hour at 350°F were in excess of foreign-promulgated hourly NO_2 standards (Canada-0.2 ppm/1 hr.), even with 2.5 acph in the kitchen and with the hood vent fan drawing 50 cfm.

COMMENT: LBL has conducted pioneering work in the evaluation and control of indoor air quality. Future work should lead from the laboratory to detailed evaluations in a variety of housing types under a variety of conditions.

COMMENTS: This study offers quantification of particle size ranges and indoor particulate concentrations. The limited study design and lack of mass/volume information (for conversion of ppcf units) tends to limit the utility of the data.

AUTHORS: Lefcoe, N.M.; Inculet, I.I.

TITLE: Particulates in Domestic Premises II. Ambient Levels and Indoor-Outdoor Relationships

SOURCE: Archives of Environmental Health 30: 565-570, December 1975

POLLUTANTS EXAMINED: Particulate (RSP), Oxides of nitrogen, Ozone, sulphur dioxide

METHODOLOGY:

- Study Design - Three test sites were examined under very controlled test conditions. Electrostatic precipitators and charcoal filters were installed in return/exhaust air ducts, and during summer months, all windows were sealed with air conditioners placed on internal air circulation only. Furnace systems (but not fuels) were noted (two gas forced-air, one hot water) along with one large potential outdoor pollutant source (auto traffic). The objectives of the study were to examine indoor and outdoor particulate, NO_2, O_3 and SO_2 levels with and without filtering systems, under normal household activities (vacuuming, cleaning, bedmaking, etc.).

- Air Sampling/Analytical Chemistry - Gaseous measurements were performed continuously for 24 hours using wet chemistry methods. No information was provided on analytical precision and accuracy or calibration procedures. Only maximum values (0 -< 2.6 pphm) were reported for SO_2, NO_2, and O_3 at living room sites and it was not clear to what extent outdoor or other indoor measurements were taken. Due to this lack of information, it is difficult to properly evaluate these measurements.

  A unique representative sampling location for particulate measurement was chosen upstream from the filter in the exhaust air duct near the furnace. Particulate was measured using a particle count analyzer with a respirable particle range of .15-.6μ. Samples were taken for one minute each hour for 24 hours.

RESULTS: Diurnal variations in particulate levels (7 a.m.-12 p.m. day, 12 p.m.-7 a.m. night) were expressed as indoor/outdoor ratios when filters and exhaust fans were used. One interesting result was a three-day average of indoor/outdoor ratios as a function of air changes per hour (ACPH) and particulate size. As the ACPH increased, particle counts in the size range of .3μ-.5μ decreased indoors, but 1.0μ particles were unaffected.

AUTHORS: Lefcoe, N.M. and Inculet, I.I.

TITLE: Particulates in Domestic Premises
I. Ambient Levels and Central Air Filtration

SOURCE: Archives of Environmental Health, 22: 230-238, February 1971

POLLUTANT EXAMINED: Particulates

RESULTS: This study involved particulate measurements in one home during daytime periods over nine days. The sampling technique (particle counts) used was identical to that used in their later study in 1975, except that no outdoor measurements were taken. Particle size distributions were seen to vary as a function of whether the electrostatic filter was on or off, and increased levels (10X normal levels to 100X normal levels correlated with increased smoking by inhabitants.

COMMENT: The lack of background (outdoor) data and air infiltration information reduces the significance of these data. As the authors point out, this represented an initial attempt to examine indoor particulate levels.

AUTHORS: Macriss, R.A. and Elkins, R.H.

TITLE: Control of the Level of NO_x in the Indoor Environment

SOURCE: Proceedings of the Fourth International Clear Air Congress, The Japanese Union of Air Pollution Prevention Associates, 1977

POLLUTANT EXAMINED: Nitric oxide (NO), Nitrogen dioxide (NO_2)

METHODOLOGY:

- Study Design - This study involved a total of sixty, 24-hour-duration measurements of NO_2 and NO levels over a one-year period in four homes, one of which was used as a control. All homes had central air conditioning, gas-fired forced-air furnaces, and gas stoves. Air infiltration rates were measured using ethane as a tracer gas, and meteorological conditions were closely monitored. The variation of the prevailing wind speed and direction during one test period, and its effect on the rate of air infiltration for each house was graphically presented.

- Air Sampling/Analytical Chemistry - No information on the calibration or quality control methods was provided for the chemiluminescent and Saltzman Technicon analyzer used in this study. The sampling locations were representative in terms of area monitoring and included a sampling site in the basement near the furnace and attached garage.

RESULTS: The NO and NO_2 levels found in the indoor environments of these four houses were shown to be generally predictable from a derived relationship of the house volume, the air infiltration rate, the amount of gas used during cooking, and the outdoor NO or NO_2 levels. While the relationship appears valid, the variables are complex and must be precisely and accurately measured. It was found that only a small portion of the 24-hour average NO_2 level can be affected by factors other than cooking and air dilution, such as absorption or other NO reaction mechanisms. Additional short-term (12-hour) studies were performed in the kitchen examining cooking episodes, NO_2 levels, infiltration rates and the effect on all of these on the stove exhaust fan at varying velocities. A 30-50% reduction of NO_2 levels was seen with the wall exhaust fan at 200-240 ft^3/min (well above the ASHRAE recommended level of 75 ft^3/min).

COMMENT: This study, although limited to four houses, was well-designed and executed. A thorough demonstration of air infiltration effects and other NO_2 eliminating mechanisms was performed. The study concluded that more work was necessary to control high short-term levels of NO_2 with hood exhaust systems.

AUTHORS: Melia, R.J.W.; Florey, C. duV; Altman, D.G.; Swan, A.V.

TITLE: Association between Gas Cooking and Respiratory Disease in Children

SOURCE: British Medical Journal, Vol. 2, 149-152, (1977)

POLLUTANT EXAMINED: Sulphur dioxide and Smoke

METHODOLOGY: No air sampling or analytical chemistry information was given, other than the fact that outdoor daily (24-hour) smoke and SO_2 levels were taken at, or around, schools with a "smoke SO_2 sampler". The authors compare their health effects data with NO_x levels from other studies, but do not report their own smoke and SO_2 observations. Consequently, the air sampling information is not necessarily representative of exposure in the study populations of gas stove and electric stove users.

COMMENT: This study is described in greater detail under the topic of health effects. The critical issue here is that personal exposures to gas stove emissions were not measured.

AUTHORS: Melia, R.J.W; Florey, C. duV; Darby, S.C.; Palmes, E.D.; Goldstein, B.D.

TITLE: Differences in NO_2 levels in Kitchens with Gas or Electric Cookers

SOURCE: Atmospheric Environment, Vol. 12, pp. 1379-81, (1978).

POLLUTANTS EXAMINED: Nitrogen dioxide (NO_2)

METHODOLOGY:

- Study Design - The three factors under investigation were cooking fuel (gas, electric), distance from the stove, and the local environment. The stated objective was to test the reliability of a new NO_2 sampler. Four kitchens were chosen: two with gas stoves, two with electric stoves. Each gas kitchen was matched with an electric one based on local environmental factors affecting NO_2 levels, including smoking habits of inhabitants, area of residence, vicinity of heavy traffic, size of kitchen, similar ventilation rates, and other sources of gas emissions. In the presentation no further elaboration of these factors was given such as: home construction and measurement of ventilation rates, maintenance conditions of the stoves, other large point sources of pollutants in the area (e.g., manufacturing, power plants) or characterization of the heating system. No ventilation hoods were used during the sampling period.

- Air Sampling Techniques - Molecular diffusion samplers were used (see below). Three samplers were used at each sampling location to measure reproducibility. The sampling sites were 2 and 7.5 ft. from the stove, and 4 feet above the floor. The sampling duration was 96 hours, of which stoves were operated 8 1/2 - 10 hours, on average.

- Analytical Chemistry - The NO_2 sampler depends on the transfer of NO_2 by diffusion to a triethanolamine (TEA) coated collector at the sealed end of a tube, when the open end of the tube is exposed to the environment. The report does not discuss the use of any techniques to eliminate possible interferences for SO_2 during sample analysis. Elimination of SO_2 by addition of hydrogen perioxide before colorimetric determination may not have been necessary but lack of information on SO_2 levels or possible sources of the pollutant (heating systems, power plants) make it difficult to determine this.

- Statistical Analysis - Means and standard deviations were generated for three values at each sampling site. Analysis of variance was performed on the three factors (fuel, distance, local environment), interaction of any two of these factors and a three factor interaction. Then a variance ratio (F-ratio) was tested for significance.

RESULTS: The hourly mean concentrations of NO_2 for gas kitchens was 72.3 ppb and 9.5 ppb ($p < 0.05$) for electric kitchens. The standard deviations of NO_2 concentrations between samplers was 1.2 ppb, which was very good. Other variables besides cooking fuel, such as, distance from the cooker and "local environment" showed no significant effects.

COMMENTS: The four-day NO_2 levels are not representative of daily or even hourly NO_2 levels and their variability over these time periods. The report takes these four-day levels and compares them to the annual arithmetic NO_2 mean of 50 ppb. These short-term measurements are too limited to be extrapolated out to an annual average. Finally, further comparative analytic NO_2 techniques (e.g., chemiluminescence) would have been helpful, but the reliability of these NO_2 samplers seems to be acceptable.

AUTHORS: Moschandreas, D.J. et al. (Geomet, Inc.)

TITLE: Indoor Air Pollution in the Residential Environment, Volumes I and II

SOURCE: EPA-600/7-78-229 a and b, Office of Research and Development, Research Triangle Park, N.C., December 1978

POLLUTANTS EXAMINED: Carbon monoxide (CO), Sulfur dioxide (SO_2), Nitrogen dioxide ($N)_2$), Nitric oxide (NO), Carbon dioxide, (CO_2), Ozone (O_3), Total non-methane hydrocarbons (NMHC), Total and respirable suspended particulate (TSP, RSP), Water soluble sulfates (SO_4-) and Nitrates (NO_3-)

METHODOLOGY:

- Study Design - Seventeen residential dwellings were monitored, each for a 14-day period. Two houses were monitored during summer and winter. A wide variety of residences were selected including residential houses, apartments, and mobile homes. All residences were in or near large urban centers and all were selected based on owner cooperation and, to a lesser extent, potential indoor and outdoor pollutant sources. In addition, data on energy parameters, infiltration rates, and family activities were obtained by observations, field experiments, and daily questionnaires, respectively.

- Air Sampling/Analytical Chemistry - Air samples were collected from four locations: one outdoor site adjacent to the buildings; and three indoor sites - the kitchen, bedroom, and living room. An integrated sampling system (3-4 in samples/hr) was used to measure CO, SO_2, NO, NO_2, CO_2; O_3, and NMHC. Twenty-four hour continuous samples were taken for TSP, RSP, SO_4-, and NO_3-.

  Throughout the study the sampling methodology was monitored for inaccurate or biased results. During initial summer sampling for SO_2, high levels of CO_2 "squelched" SO_2 levels in the flame photometric sampling method. This CO_2 interference problem was subsequently corrected in a later sampling when the H_2S scrubber was rebuilt. Another possible bias due to sampling loss in long sampling lines was examined by a short experiment using 10-foot and 100-foot sampling lines. No significant sample loss was seen between either sampling line for all pollutants. Of additional interest was the use of a dicotomous RSP sampler with a 2.5μ mean mass diameter cutoff point, and a qualitative characterization of episodic releases of furniture polish and oven cleaner. This latter sampling was performed with Tenex tubes and analyzed by gas chromotography and mass spectrophotometry.

- Statistical Analysis - A one-zone concept was used for summation of the large data base. The hourly pollutant concentrations for each indoor sampling location were averaged to provide an overall indoor hourly concentration for each pollutant. The first step in forming this indoor hourly average was to rest statistically for differences (period t-test) between the indoor sampling locations. The authors concluded, "Corresponding hourly indoor pollutant concentrations are not uniform throughout a residence, but the existing differences between sampled indoor sites are small and probably of minimal health significance." Currently, there is no data on the associated health effects of peak concentrations of these pollutants and this data interpretation precluded any analysis of these peak concentrations altogether. The analysis of the small differences between indoor sites was subject to interpretation. From the one statistical survey of t-tests presented, the majority of the means (mean of differences) were small between indoor sampling locations. However, there were exceptions, such as the mean of the differences between NO_2 levels for the kitchen and bedroom which was 0.67 ppm. This value is very significant when compared to the recommended hourly NO_2 average of 0.25-0.5 ppm.

  The question of the importance of pollutant gradients indoors is very controversial, and this report presents one method to evaluate these gradients. Their conclusions are based on a statistical analysis between indoor sampling sites, tracer studies and the air exchange rates in each residence. If subsequent one-zone data summaries were executed in the same manner then, in the absence of personal sampling, this method should characterize pollutant exposure for inhabitants confined all day long to their homes. Application of the one zone concept based on one indoor hourly measurement and no air exchange data would not be representative of indoor levels.

  High indoor/outdoor ratios of pollutant concentrations were seen for CO, NO, NO_2, and CO_2. Ten residences with gas appliances showed high indoor levels of CO, NO, NO_2 and NMHC as compared to those with electric appliances (2 residences measured twice). In a few cases, CO levels exceeded the EPA standard of 9 ppm for 8 hours but the majority of the CO levels were between 2.3-6.0 ppm for 8 hours. In addition, periodic indoor levels of O_3, TSP and NMHC exceeded daily standards. The data for RSP, $SO_4^=$ and NO_3^- was generally inconclusive with daily levels ranging from 1-9 $\mu g/m^3$, 1.5-48.3 $\mu g/m^3$ and 1.0-6.0 $\mu g/m^3$, respectively. A positive correlation was seen between the presence of young children or heavy smokers and daily RSP levels.

COMMENTS: This study involved a comprehensive monitoring and characterization of indoor air quality and it contributed significantly to the data base for indoor pollutants. The quality control methods to eliminate calibration error and observer error were well-documented. One negative aspect of this study was the lack of definition for associations of indoor pollutant sources and pollutant levels which limited the conclusions to only gross comparisons between gas and electric appliances. For example, high CO levels were attributed to gas sources indoors, but these levels could have been associated with gas appliances, attached garages, faulty furnaces or smoking habits. Also, as pointed out above, there were only two all electric houses (monitored twice each) in the study as opposed to twelve houses with either gas stoves or furnaces.

AUTHORS: Palmes, E.D. and Tomczyk, C.

TITLE: Relationship of Indoor NO_2 Concentrations to Use of Unvented Gas Appliances

SOURCE: Journal of the Air Pollution Control Association, Vol. 29 (4) 392-393, April 1979

POLLUTANT EXAMINED: Nitrogen dioxide (NO_2)

METHODOLOGY:

- Study Design - Twelve homes with unvented gas appliances were monitored for hourly NO_2 levels during a one-week period. Outside pollutant sources and infiltration/ventilation rates were not characterized in the rural Florida area where the homes were located.

- Air Sampling/Analytical Chemistry - Air sampling was performed using the Palmes passive NO_2 monitor. This method does not detect peak NO_2 levels which are common when gas appliances are first turned on. Residents were given precise instructions for placement of the samples. There was no quality control for this method of sampling and no explanation of analytical calibration or standardization. Although these NO_2 samplers were originally intended to measure personal exposures, in this study they were used for area monitoring for comparison to ambient standards.

RESULTS: The results are presented separately as averages for an unvented stove, an unvented space heater, an unvented stove and heater, and two unvented heaters. The stoves and/or heaters with separate monitors were located in separate rooms and one room with neither a stove or heater was also monitored. The highest hourly NO_2 levels were seen in the homes with the unvented stove and space heater (130 ppb).

COMMENT: This study represents a preliminary effort to characterize this relationship. Further characterization of other NO_2 sources should result in a larger data base over a larger time-span and under various conditions so that more accurate comparisons can be made to annual standards.

AUTHORS: Phair, J.J., R.J. Shephard, G.C.R. Carey and M.L. Thomson

TITLE: The Estimation of Gaseous Acid in Domestic Premises

SOURCE: British Journal of Industrial Medicine 15:283-291, 1958

POLLUTANT EXAMINED: Gaseous Acid (SO_2)

METHODOLOGY:

- Air Sampling/Analytical Chemistry - An early gaseous acid wet-chemistry integrated sampling method is described and then tested in the field. A hydrogen peroxide solution was placed in six impingers which were exposed to the atmosphere on an hourly basis for six hours by a solenoid valve followed by a manual switch over to the next six impingers. Samples were analyzed in the laboratory by the conductivity method. Factors affecting the rate of sampling and evaporation of absorbent solution are critically evaluated. Design modifications were made to account for variations in flow rate, evaporation (a reduced temperature in the sampling box eliminated this) and sampling loss in the sampling lines (diameter, shape, length of the tubing and leakage at impinger caps). Calibration of the conductivity apparatus (± 1%) and flow rate (standard error was ± .075 ℓ/min) were thoroughly conducted.

RESULTS: Measurements of the non-specific gaseous acid levels were taken daily indoors and outdoors over two months at various geographical locations in Cincinnati. Indoor measurements indicated a general tendency to follow outdoor readings with a lag of two hours; however, indoor concentrations of gaseous acid were on the average much lower, and did not show the sharp peaks seen at outside locations. Significant gradiants of gaseous acids were identified.

COMMENTS: Although the indoor and outdoor pollutant sources were not described and the pollutant index was non-specific for gaseous acids, the gross results are consistent with other studies. More accurate and less complex analytical techniques are available today, but the issues and problems the authors approached here are characteristic of current problems in air sampling methodology. This was a sound well-executed study for integrated air sampling, serving as the foundation for current integrated sampling methods.

AUTHOR: Schaefer, U.J. et al.

TITLE: Air Quality in American Homes

SOURCE: Science, 173-175, 14 January 1972

POLLUTANT EXAMINED
EXAMINED: Particulate (Sedimentation)

METHODOLOGY:

- Air Sampling/Analytical Chemistry - More than 100 homes were evaluated for particulate sedimentation levels in four regions of the country (USA) during four different seasons. Strips of aluminum foil coated with a silicone adhesive were placed inside or outside homes for a period of one month. Results were reported as average mass per foil.

RESULTS: There was a correlation (0.7) between average mass per foil measured indoors and annual geometric outdoor particulate levels (mg/m^2). However, the outside levels did not have similar geographical distribution as the indoor measurements. Further detail is necessary to determine exactly what these indoor outdoor levels represent. Higher levels were reported in bathrooms and kitchens. The authors make an association between these levels in kitchens and gas and electric stoves. This sampling method is so dependent on the foil location and human activity that only qualitative observations are possible.

COMMENT: This must be considered an early pioneering attempt to identify gross indoor/outdoor relationships.

AUTHORS: Spengler, J.D., D.W. Dockery, W.A. Turner, J.M. Wolfson, and B.G. Ferris.

TITLE: Long-term Measurements of Respirable Sulfates and Particles Inside and Outside Homes

SOURCE: Presented at the 72nd Annual Meeting of the Air Pollution Control Association, Cincinnati, OH, 24-29 June, 1979.

POLLUTANTS EXAMINED: Sulfur dioxide (SO_2) Nitrogen dioxide (NO_2), Mass Respirable Particulate (MRP) and Sulfate Fraction

SUBJECT: This is an update and review of Harvard's six-city prospective epidemiological study to assess respiratory health effects of particulate and sulfur oxides. Discussions focus on the air monitoring method.

METHODOLOGY:

- Study design - Homes were selected based on two criteria; uniform geographic locations of homes across city and representative samples of the range of home characteristics in the community. Variables that could affect indoor pollutant levels (smoking, cooking and heating fuel, type of ventilation) were documented, although infiltration rates were not specifically measured.

- Air Sampling/Analytical Chemistry - A three-stage air monitoring system was used to build an exposure index for participants in the study. The three components were: continuous ambient monitoring at a central site; an array of indoor/outdoor satellite monitors in homes across the community; and finally, on a limited basis, personal monitoring. The indoor area samples are only represented by one sampling site which does not account for spatial peak pollutant levels throughout the house. However, if these indoor samples are used in conjunction with personal samples, a representative exposure index could be constructed.

RESULTS: Only results of the central site and indoor/outdoor area sample are reported here. Annual and monthly pollutant levels were evaluated for significant trends. Sulfate concentrations were fairly evenly distributed across any particular city. SO_2, NO_2 and MRP indoor/outdoor levels were significantly influenced by indoor sources. NO_2 indoor concentrations showed that populations using gas appliances in a clean city can have NO_2 exposures similar to those of a population using electric appliances but living in a more polluted city.

COMMENTS: The large size of this study and the comprehensive nature of the air sampling should account for personal exposure and spatial distributions of pollutants. The final results could significantly add to the quantification of indoor levels. However, if indoor/outdoor area monitoring rather than personal monitoring is used to represent the exposure index, it will be more difficult to evaluate the relationship between exposure and long-term health effects.

AUTHORS: Sterling, T.D. and E. Sterling

TITLE: Carbon Monoxide Levels in Kitchens and Homes with Gas Cookers

SOURCE: Journal of Air Pollution Control Association, Vol. 29 (3), pp. 238-241, March 1979

POLLUTANTS EXAMINED: Carbon monoxide (CO)

METHODOLOGY:

- Study Design - This study was performed in two phases: 1) short-term levels of CO were measured at one house to determine the growth and dissipation of CO under various normal conditions of cooking (with and without pans, number of burners) and ventilation (exhaust fan and open/closed windows); 2) short-term levels (90 minutes) of CO were measured in nine homes with gas stoves at various times after 20 minutes of burner use in the kitchen, dining room, living room and outside. Infiltration rates and pertinent meteorological conditions affecting these rates and CO measurements were not documented. No additional indoor pollutant sources (furnace type) or outdoor pollutant sources were characterized to evaluate their influence on the measured CO levels.

- Air Sampling Technique/Analytical Chemistry - In the first phase, CO sampling was performed using an Ecolyzer every 2-5 minutes for a ninety-minute period. In the second portion, samples were taken at 0, 30, and 90 minutes after the cooking period. It is not clear whether one instrument was in a fixed location at each sampling point or one instrument was moved from location to location for a grab sample.

RESULTS: When the pan was placed over the flame there were significant increases in CO production for a 30-minute period. A high negative correlation (-0.7) was demonstrated between the rate of CO increase (determined by least square approximation of all data points for each house separately, exclusive of outdoor levels) and inside volume of the house. As expected, this rate of increase was very dependent on ventilation rates.

The authors compare their results to recommended CO air quality standards for 8 hours. Unfortunately, a 90-minute sampling period is not very representative of 8-hour CO levels.

COMMENTS: Without more information on the sampling method, evaluation of the representativeness of the CO levels is difficult. It is clear that those short-term CO levels cannot be extrapolated to a long-term exposure to CO.

AUTHORS: Thompson, C.R., E.G. Hensel, G. Kats

TITLE: Outdoor-Indoor Levels of Six Air Pollutants

SOURCE: Journal of the Air Pollution Control Association, Vol. 23 (10), pp. 881-886, October 1973

POLLUTANTS EXAMINED: Total oxidant (O_3), Peroxyacetyl nitrate (PAN), Nitric oxide (NO), Nitrogen dioxide (NO_2), Carbon monoxide (CO) and Particulate (TSP)

METHODOLOGY:

- Study Design - Several kinds of structures were selected for this study (hospitals, schools, commercial buildings, and homes) based on various types of air conditioning systems (refrigeration, evaporative cooling) and primary and secondary filtration equipment. Air exchange rates (acph) and pollutant levels were measured for one day for which specific meteorological conditions were detailed. The objective of the study was aimed at outdoor pollutant activity and its infiltration to indoor spaces, consequently, no information was provided on potential indoor pollutant sources.

- Air Sampling/Analytical Chemistry - Only O_3 and particulate sampling was performed continuously indoors and outdoors. Sampling for CO, NO, NO_2 and PAN was conducted at each site, inside and outside, at 15-minute intervals with grab samples (mylar bags or 100 cc syringes). This is an outdated technique which suffers from heavy sampling bias as compared to current integrated or continuous sampling techniques. In addition, sampling for NO and NO_2 was performed using the conductivity method.

RESULTS: A substantial reduction in particulate levels was seen in those buildings with refrigerated air conditioning and filtration, especially the one home with an electrostatic filter. O_3 levels inside depended upon infiltration from outside and residence time in the structure.

COMMENTS: Due to the grab sampling techniques for CO, NO_2 and PAN, the only significant results are those for O_3 and particulates. The results for these two pollutants were qualitatively correlated with outdoor levels and building conditioning equipment with no attention focused on potential indoor sources.

AUTHORS: Yocum, J.E., W.A. Cote, W.L. Clink

TITLE: A Study of Indoor-Outdoor Air Pollutant Relationships, Volume I

SOURCE: DHEW, PHS, EHS, National Air Pollution Control Administration Technical Center, Contract No. CPA 22-69-14, Durbarer, N.C., May, 1970

POLLUTANTS EXAMINED: Suspended Particulate (total and respirable), Soiling particulate matter, Carbon monoxide (CO), and Sulfur dioxide (SO_2).

METHODOLOGY:

- Study Design - The object of the study was to measure concentrations of the four different pollutalnts (during summer, fall, and winter) simultaneously at four locations in and around three pairs of structures, and to evaluate various building parameters that may affect indoor and outdoor air quality relationships. Three basic types of structures were used for the study: public buildings, office buildings, and private homes. Structures in each pair were essentially similar, except for design features which might affect the concentration of certain pollutants (e.g., one office building was on top of a parking garage, open windows in relation to major auto traffic in public buildings, and different occupancy of the private homes). Geographical location of each pair was chosen with respect to highways (traffic patterns) and large point sources which may affect pollutant levels.

  The buildings were well-characterized in terms of construction, maintenance, and local meteorological conditions. Only a partial inventory of potential indoor pollutant sources was performed. The heating systems of all buildings and cooking activities of residents were not mentioned.

- Air Sampling Technique/Analytical Chemistry - For each building four sampling locations were chosen and labeled: far outside, near outside, near inside, and far inside. TRC designed two self-contained portable instrument packages located outdoors with five sample lines per sampling site connected to a central vacuum pump with a solenoid valve to alternate sampling points. Sampling times at each point were: CO and SO_2 - 5 minutes (3 times/hr); soiling particulate - 2 hours (3 times/day); and particulate sampling - continuous 24 hours. This integrated approach to air sampling allows for some characterization of peak concentrations of pollutants, but is very dependent on pollutant decay rates and any secondary reactions which affect their concentrations. The advantages of this technique are less equipment for transport and maintenance and less analytical variation between instruments.

The quality control and calibration of analytic instrumentation for CO (infrared) and TSP (gravimetric) were well-documented. However, instrumentation problems affected measurements, causing random data losses for the qualitative soiling index (Gelman paper tape), RSP (Roesler method) and SO_2 (conductimetric analyzer). Due to disintegration of the polyurethane prefilter onto the sample, the RSP sampling was repeated in the fall and winter with an Anderson sampler for selected 3-day periods. The SO_2 conductimetric analyzer was affected by CO_2 interference at low levels of SO_2 due to a poor scrubbing system.

As in other projects of this size that involve measurements over extended time periods, "state-of-the-art" sampling techniques were often modified or abandoned. The authors did an excellent job of documenting these changes. Unfortunately, however, the modifications caused a variety of unequal sampling periods for pollutants (two weeks, one week and 3 days) and this limits the representativeness of the data.

- Statistical Analysis - The large body of data was summarized by using arithmetic averages of pollutant levels over 12-hour periods. Diurnal variations in pollutant levels were presented as ratios. Trends in the levels from far outside to far inside were also examined to identify pollutant gradients. When far inside/far outside ratios were greater than one, it was assumed that indoor pollutant sources were responsible.

RESULTS:

An overall survey of the ratios of inside to outside concentrations indicates that particulates penetrate structures least readily, and SO_2 suffers some loss during penetration. Indoor CO levels are a result of rapid penetration from outdoors as well as contributions from indoor sources.

The authors discuss the influence of activity patterns and traffic and seasonal factors on TSP levels; however, in the fall and winter only, weekly measurements for TSP were made. Organic fractions of TSP and CO measurements had high inside/outside measurements but potential indoor sources and ventilation rates were not studied.

COMMENTS: In general, the study met its first objective to characterize indoor and outdoor pollutant levels, but its secondary objective to identify building parameters that affect these levels was not achieved due to the limiations in the data base (varying sample durations, incomplete characterization of ventilation rates and indoor sources, and analytic instrumentation problems).

AUTHORS: Yocum, J.E., W.A. Cote, W.L. Clink

TITLE: Volume II - A Study of Indoor-Outdoor Air Pollutant Relationships

SOURCE: DHEW, PHS, EHS, National Air Pollution Control Administration Technical Center, Contract No. CPA 22-69-14, Durbarer, N.C., May, 1970

POLLUTANTS EXAMINED: Carbon monoxide (CO), Sulfur dioxide (SO_2), and Soiling particulate

METHODOLOGY:

- Study design - This was a preliminary study to test the sampling methodology and to study comparative indoor and outdoor concentrations of selected pollutants (CO, SO_2, soiling particulate) at four single-family dwellings; two with natural gas, two with coal-fired heating systems. Potential outdoor sources of the pollutants and meteorological conditions were characterized and the indoor sources of pollutants, heating systems and stoves at various operating conditions weredescribed.

- Air Sampling Techniques/Analytical Chemsitry - Only CO was measured in the homes with gas stoves and heating systems. CO, SO_2, and soiling particulate were measured in those with electric systems. Sampling techniques and analyses were identical to those reported in Volume I. The only change was that 3 indoor and 1 outdoor sampling locations were used in the gas-fired systems. The sampling periods were for 48 hours.

- Statistical Analysis - Measurements of gaseous pollutants (CO and SO_2) are plotted graphically as hourly average (three- to five-minute bits) concentrations (ppm). Soiling particulate is based on two-hour samples.

RESULTS: Qualitative observations covering the 48-hour period are made for each home with respect to indoor and outdoor human and automobile traffic patterns. Examples of some conclusions are: The gas-heated homes had no effect on CO levels but gas-fired stoves did; attached garages with common doors to the house are sources of CO inside houses as are coal-fired hot-air heating systems with apparent leaks. One house had hourly CO measurements at 35-60 ppm and SO_2 at .40-.80 ppm over a five-hour period. These levels exceed EPA standards for CO (one hour) and SO_2 (three hours), but not eight-hour TLV's (comparison here is difficult due to the integrated area sampling method). No health effects of inhabitants were documented.

COMMENTS: These conclusions are general observations limited in their specific application to health effects and standards, but useful in preliminary characterization of indoor/outdoor air quality with respect to indoor pollutant sources.

APPENDIX II

HEALTH EFFECTS OF INDOOR AIR POLLUTION

ANNOTATED BIBLIOGRAPHY OF SELECTED STUDIES

AUTHOR: Eaton, W.C., C. Shy, J. Finklea, J. Howard, R. Burton, G. Ward, F. Benson

TITLE: Exposure to Indoor Nitrogen Dioxide From Gas Stoves

SOURCE: Human Studies Laboratory, National Environmental Research Center, Environmental Protection Agency, Research Triange Park, North Carolina, Revised January 1973.

DATA COLLECTION: Two different data collection activities and analyses are described in this manuscript. Longitudinal data on the incidence of respiratory disease were obtained from 146 families in a suburban fringe community on Long Island. From October 1970 through May 1971, each family was questioned once every two weeks about common respiratory ailments. No information was given about how the 146 families were selected. Eighty-seven of the families used gas for cooking and 59 did not.

According to the authors, the two groups had similar numbers of cigarette smokers and similar numbers of families who had changed their address in the past five years. The families using gas stoves appeared to be somewhat better educated.

The second data collection activity took place in a gas-cooking kitchen in Durham County, North Carolina. Levels of NO, NO_2, NO_x, and CO were measured at various times and locations. Concentrations near the stove were measured for each meal preparation over a one-week period. A decrease in NO_2 concentration away from the stove was observed for six stove usages. A controlled test to examine NO, NO_2, and NO_x concentrations across time was done. Another test studied maximum concentrations as the gas flow rate varied.

ANALYSIS AND RESULTS: Each family member was classified as a mother, father, school child, or pre-school child. Except for pre-school children, a "significantly" higher incidence of acute lower respirtatory illness was found in the gas-cooking homes. The rates per 100 person-weeks varied from approximately 1.80 for fathers to approximately 4.6 for pre-schoolers. Samples sizes were given as number of person-weeks of data. These varied from 1710 to 5400. Apparently, no control (other than type of family member) variables were considered in the analyses.

Analysis of the concentration of nitrogen oxides data showed clearly that concentrations of NO, NO_2 and NO_x all rise substantially near the stove when it is being used. Concentrations prior to gas burning were .01 ppm for NO and .00 ppm for NO_2. During meal preparation, the NO_2 concentration rose to maximum levels ranging from .20 to 1.0. The increase six feet from the stove was not nearly so great, however, ranging from .05 - .20 ppm when the corresponding readings at the stove ranged from .30 - .70 ppm.

A single sixty-minute burning showed that oxide levels rise rapidly for about 30 minutes and then level off. After putting out the flame, an hour passed before the concentration decreased to the earlier level. Concentration of all nitric oxides increased with the flow rate of the gas. The highest observed CO concentration was 3.7 ppm. No other information on CO concentration was included.

COMMENTS: This study is consistent with those of other investigators in finding that burning gas increases the concentration of nitric oxides. Even though it is based on one home only, the positive effect is clear.

The statement that levels of acute lower respiratory illness are "significantly" higher in gas-cooking homes for three segments of the population is absolutely not true. The observed differences do not even approach statistical significance.

The data given in the figure (below) are sufficient to allow construction of contingency tables, such as the one presented below for fathers.

	Gas Cooking	Not Gas Cooking
Person-weeks reporting illness	42	29
Person-weeks not reporting illness	2208	1681

The numbers in the top row were found by multiplying the reported illness rate (in decimal form) by the reported sample size. The number of person weeks for which no illness was reported can be obtained by subtraction. We calculated a standard χ^2 statistic for testing the null hypothesis that illness rate is independent of cooking fuel. The value for this χ^2 was 0.16 as compared to a value of 3.84 that is required for significance at the 5% significance level. There is no evidence to indicate an important relationship between cooking fuel and reported illness. Values of χ^2 for the other three segments were 1.75 (mothers), 0.67 (school children), and 0.06 (preschoolers). All of the data are consistent with the hypothesis that the illness rate is the same in gas cooking homes as in non-gas cooking homes.

(Technical note: The above hypothesis test is technically valid only if the data consist of indpendent observations. In fact, they are not independent because repeated measurements were obtained from 146 families over a seven-month period. Presumably within-family measurements may be correlated with each other. The effect of the correlation is to reduce the effective sample size and increase the variance of parameter estimates over what would be obtained with independent observations. As a result, the values of the above test statistics are probably overstated and the association is even weaker than it appears.)

<u>SUMMARY</u>: Results concerning respiratory illness were found to be quite consistent with the null hypothesis that illness rate does not depend on the type of cooking fuel. This contradicts the authors' statement that significantly higher levels of illness were found in gas homes for three family-segments.

Separate measurements confirmed that nitric oxide concentrations are higher in kitchens with gas cooking stoves.

AUTHORS — Keller, M.D.; Lanese, R.; Mitchell, R.; Cote, R.

TITLE — Respiratory Illness in Households Using Gas and Electricity for Cooking, 1. Survey of Incidence

SOURCE — Environmental Research 19: 495-503, 1979. Also reported by Lutz, G.A., Mitchell, R.; Cote, T.; Keller, M.; "Indoor Epidemiology Study," American Gas Association, 1977.

DATA COLLECTION

Epidemiological Data

Volunteer families were contacted through the elementary schools of Upper Arlington, Ohio, a middle class suburb of Columbus. Special follow-up efforts were necessary to obtain enough families with gas cooking stoves. The sample included 232 electric-cooking households and 209 gas-cooking households. All families expressed willingness to participate for an entire year. An initial self-administered questionnaire obtained data describing the parents, the children under 12, and demographic information about the household.

Parents were asked about smoking history and current respiratory symptoms. They reported on the respiratory illness history of each child and provided occupation of head of household, race, time of residence in current town, size of living quarters, type of cooking stove, and use of gas space heater. Bi-weekly phone calls were made to each family for 26 periods to obtain data on the incidence of new respiratory symptoms for each family member.

Forty-two percent of the population consented to participate in lung function testing in which FVC and $FEV_{0.75}$ were measured.

NO_2 Measurements

Eighty-three gas cooking homes and 50 electric cooking homes were monitored to obtain 24-hour NO_2 and NO concentrations. No mention is made of what rooms were monitored. Fifty-three outdoor measurements were made. Three-day continuous measurements were obtained from 46 homes. Except for noting that both peak and average NO and NO_2 concentrations are higher in gas homes, the analysis of these data was not described here.

ANALYSIS OF EPIDEMIOLOGY DATA

Most of the analysis focused on the prospective data concerning incidence of new respiratory illness. An incidence rate, standardized to rate/hundred persons/year was calculated for each person. Comparisons between persons in gas-cooking and electric-cooking homes were made separately for mothers, fathers, and children under 12. Incidence of "all respiratory disease" was the primary outcome measure, although lower respiratory disease was studied for mothers. Uncorrected incidence rates for all comparisons were slightly higher in electric-cooking homes.

Some limited comparisons between the questionnaire data for gas and electric homes were reported. The comparisons indicated that a few more gas-cooking fathers were smokers, and that the electric-cooking households may have a slightly higher soci-economic status as measured by education and number of rooms in the living quarters. It is not stated whether the responses to other questions were also comparable. If the two groups really are comparable, then the uncorrected incidence rates will accurately reflect any association between cooking mode and respiratory illness.

An analysis algorithm called Automatic Interaction Detectory (AID) was used to analyze the incidence data. This technique is usually quite powerful at detecting relationships between an ordinal-valued outcome variable (such as incidence rate) and potential predictor variables. In this case, no important predictors of respiratory illness were identified for any of the groups mothers, fathers, and children. Some potentially important predictors may have been omitted, however. For mothers and fathers, age, cooking mode, chronic respiratory symptoms, and smoking history were all entered. The surrogate social class variables of education and size of living quarters were omitted, however. These variables were entered for the children, but parental smoking was not. This seems a rather crucial oversight (Multiple regression, not AID, was used to analyze children's data.)

The analysis was repeated with data from Long Island mothers that had been collected in a similar fashion. Again, no important predictors were identified.

ANALYSIS OF LUNGFUNCTION DATA

Forty-two percent of the study group, or 822 of the 1952 participants agreed to participate in lung function measurements. A χ^2 analysis was done which ascertained that the age-sex distributions of the participants from the gas-cooking and electric-cooking households were not significantly different from each other. No test was done, however, to determine if the participants appear to be a representative sample from the entire study population. The data in Table 3 indicate that they are not. Very young children (0-5 years) and late teens (16-20 years) appear to be underrepresented in the group that participated in the lung function measurements.

The lung function data were adjusted for age, height, and weight using analysis of covariance. Adjusted means were then compared for the gas-cooking and electric-cooking groups. The results showed no difference for FVC and that the gas-cooking group was slightly higher for FEV-75. No other covariates, particularly those relating to smoking, were used in this analysis. Apparently all age groups, adults and children, were included in one analysis.

COMMENTS

This study suffers from several methodological flaws both in the design and analysis, but it is not possible to ascertain whether these have any effect on the outcome. Although the paper by Keller, et al. in Environmental Research refers to a "random" sample of families, this is clearly a volunteer sample of families from a specific homogeneous environment. Whether these results apply to other cities, social classes, environmental conditions, or even the families that chose not to participate cannot be determined.

Data were collected on cards that were color-coded to distinguish gas-cooking households from electric-cooking households. In other words, this was not a "blind" study. The possibility of interviewer bias cannot be ruled out under these circumstances.

It is surprising that no variables were identified that correlated with incidence of respiratory disease. Although the sample sizes were a little small to justify the use of AID (the authors of AID recommend at least 1,000 observations), this is a quite powerful technique for identifying relationships. The fact that some variables which have been important in other studies were not included may explain some of this. Omitting the parental smoking variable for children seems a rather serious oversight. Perhaps the homogeneous nature of the volunteer study sample is a partial explanation for the lack of predictive power.

While the analysis of the lung function data is correct in principle, its execution may be improved. Using a single adjustment equation for all respondents, children and adults, seems unwise. It is quite likely that different adjustments are necessary for different age-sex groups. Sex was apparently not considered and a linear adjustment for age is unlikely to be appropriate. Beyond these adjustments, smoking (for adults) and parental smoking (for children) have been significant correlates of lung function in other studies. Leaving these out reduces the precision of the results (at best) and may introduce a bias. Again, the selection bias from using a volunteer sample may affect the results.

SUMMARY

The study showed no harmful effect of gas-cooking on lung function or incidence of new repiratory disease. Several methodological problems reduce the credibility of the results. These include use of a volunteer sample, possible interviewer bias, use of inappropriate covariance procedures, and omission of important covariates. The effect on the results of these shortcomings cannot be determined.

AUTHORS Keller, M.D.; R. Lanese; R. Mitchell; R. Cote

TITLE Respiratory Illness in Households Using Gas and Electricity for Cooking, II. Symptoms and Objective Findings

SOURCE Environmental Research 19:504-515, 1979.

DATA COLLECTION

The purpose of this study was to confirm the incidence and reported symptoms of those reporting respiratory illness. This was done by having a nurse-epidemiologist examine a subsample of those reporting illness and a subsample of matched controls.

A subsample of 60 gas-cooking households and 60 electric-cooking households was selected from the households that participated in the earlier study. They were selected on "a basis of reasonable demographic match and history of participation." Telephone interviews with the participating families were conducted every two weeks for 13 months, During each interview, information was collected concerning incidence of new respiratory illness and specific symptoms and activity restrictions for all those reporting an illness.

An appointment was made for the nurse-epidemiologist to visit the household of most persons who reported an illness onset within three days prior to the call. Since no visits were made on weekends, some of the new illnesses could not be followed in this manner. In addition to examing the person reporting the illness, the nurse-epidemiologist also attempted to examine two control persons--an ostensibly well person from the same household and another person from a "well" household utilizing the same cooking fuel.

The study sample consisted of 586 persons. A total of 1248 respiratory illnesses was reported during the 13-month period. Of these, 268 qualified for visits because the onset was within three days of the call. Because no visits were made on weekends and other forms of nonresponse, 175 visits were actually made. Apparently useable data were obtained from 150-163 of these persons (see Table 2). The number of controls used in the analysis was smaller: 102-106 same household controls and 84 controls from other households.

DATA ANALYSIS AND RESULTS

The first analysis segment reported the occurrence of specific symptoms found during the examination of those reporting illness and the control groups. Of those reporting an illness, 93% exhibited at least one respiratory symptom while approximately one-third of the controls did. Overall, same household controls and other household controls showed the same rate of respiratory symptoms. The results of throat cultures showeda somewhat higher occurrence of pathogens among those reporting illness.

The bulk of the remaining analysis was examining the incidence of respiratory illness and symptoms as reported by the respondent. None of the comparisons between gas-cooking and electric-cooking households were adjusted for any covariates. Comparisons were made separately for each of four kinds of family members: fathers, mothers, children 12-18, children under 12. Uncorrected incidence rates of reported respiratory illnesses were slightly higher in electric-cooking households for all types of family members. The percentage of household members reporting at least one illness during the period was significantly higher in electric-cooking households for children 12-18. Although this percentage was higher for mothers in gas-cooking households, none of these differences were large. The distribution of number of illnesses per person were compared using χ^2 test, but no differences were found.

Comparisons of the occurrence of different reported symptoms showed little difference. More "tearing or redness of eyes" was reported for electric-cooking households and more frequent physician consultation among gas-cooking households. Separate comparisons for upper and lower respiratory illness, fever, and days lost from work or school showed no differences between the cooking modes.

Sensitivity ard specificity of the telephone interviews for detecting illness were calculated as 72% and 91%, respectively.

COMMENTS

This study is not a replication or validation of the authors' earlier study. This study shows that if one continues measurements on the same group of respondents, then one continues to get the same results. To "replicate" the results would involve selecting a new community in order to show that these results are not specific to the original community. Since this was not done, we have no basis on which to generalize these results. Comments concerning sampling and interviewer bias, made in the previous review, should be considered here.

Statistical analysis, while unsophisticated, appears to be reasonably appropriate if these families could be considered a random sample from some population. A more sophisticated analysis would be difficult with this limited sample size, but ignoring covariates does reduce the sensitivity of the tests and may introduce bias.

The authors did not compare the results of the positive examination findings for the controls from the gas-cooking and electric-cooking homes. Although the sample sizes are limited, examination of Table 2 (Environmental Research, 1979, p. 507) shows that "redness of nasal mucosa" and "redness of conjunctivae" occur much more frequently in gas-cooking households while "redness of throat" appears to be more prevalent in electric-cooking households. (Small sample sizes make exact tests of these findings difficult.) Table 4 gives percentages of cultures yielding specific organisms. Overall, these pathogens are more prevalent in the electric-cooking households, particularly among those reporting illness and controls from other households. That there is no difference in the "same household controls" seems curious. Hemophilus, in particular, was much more prevalent in the electric-cooking households.

VALIDITY OF TELEPHONE REPORTING OF RESPIRATORY ILLNESS

In-home examinations to verify reports of respiratory illness were conducted for 175 persons who reported illness and 188 controls. The results of the nurse-epidemiologist's examinations are shown in the table below, which is Table 12 (p. 514, Environmental Research, 1979).

		Positive Findings		
		Yes	No	Total
Reported Illness	Yes	163	12	175
	No	64	124	188
	Total	227	136	363

By direct calculation from the table, the authors estimate sensitivity as 163/227 = .718 and specificity as 124/136 = .912.

These calculations are not appropriate, however, because those reporting an illness were heavily over-sampled relative to those not reporting an illness. Earlier in the paper it was reported that 1248 respiratory illnesses were reported out of 15,325 person-responses. This leaves 14,077 person-responses for which no illness was reported. The examinations of the 175 reported illnesses represent 14% of the 1248 illness reports, while the examinations of the 188 controls represent only 1.3% of the "no illness" responses.

To correctly assess the sensitivity and specificity of the reporting method, the different sampling rates for the two groups of responses must be taken into account. The easiest way to do this is to estimate what the results would be if examinations had been done for every person response. Since 163/175 = 93.1% of those reporting illness had positive findings, we estimate that (.931) (1248)≈ 1161.9 of the 1248 illness reports would result in positive findings. Similarly, since 64/188≈ 34% of the controls had positive findings, we estimate that (.34) (14077)≈ 4786.2 of the "no illness" responses would have positive findings, if examined.

The table of estimated results for all 15,325 person-responses is given below.

		Positive Findings		
		Yes	No	Total
Reported Illness	Yes	1161.9	86.1	1,248
	No	4786.2	9290.8	14,077
	Total	5948.1	9376.9	15,325

Appropriate estimates of the sensitivity and specificity can be made from this table. The sensitivity of the telephone reports is estimated to be 1161.9/5948.1 = 19.5%. In other words, the false negative rate of the telephone reports (using examination results as the standard) is 80.5%. This is because over a third of the "no illness" responses showed positive findings upon examination. The correctly adjusted specificity results are more encouraging. The estimated specificity is 9290.8/9376.9 = 99.1%. A person who is not ill (by examination) is very unlikely to report being ill in a telephone interview.

In summary, the telephone interviews are not very sensitive; persons who yield positive findings upon examination are more likely to report that they are not ill than that they are ill. As a result, we expect that the interviews would correctly identify only 19.5% of those who actually have symptoms of respiratory illness. On the other hand, almost all of those who show no symptoms upon examination would report that they are not ill.

Unfortunately, these findings cast some doubt on the usefulness of telephone interviewing for correctly identifying those who show positive symptoms of respiratory illness. The time lag between the telephone report and the examination may account for some portion of this discrepancy, but this explanation is unlikely given the overall low incidence of reported respiratory illness. Other reasons for the difference may be offered. The examination method may be too sensitive. The fact that one respondent reported for the entire household may also lead to misclassifications. People may be more aware of their own symptoms than those of their family. It would be interesting to see if different response patterns are observed for the respondent than for other family members.

SUMMARY

This study, partially a follow-up of the authors' previous work, indicated little difference in reported respiratory illness for gas-cooking and electric-cooking households. All of the caveats applied to the earlier study--possible sampling bias, possible interviewer bias, omission of covariates from the analysis, etc.,--should also be considered here. Follow-up examinations were conducted for a sample of those reporting illness and also a sample of controls. Due to an inappropriate analysis, the authors seriously overestimated the sensitivity of telephone interviews for identifying those with positive symptoms of respiratory illness.

AUTHOR: Melia, R.J.W., C. Florey, D. Altman, A. Swan

TITLE: Association between Gas Cooking and Respiratory Disease in Children

SOURCE: British Medical Journal 16:149-152, 1977

DATA COLLECTION: A stratified random sample of 28 government exchange areas in England was selected in 1972. Poorer areas were oversampled. Within these areas a sample of primary schools was selected. Attempts were made to collect data on all children aged 6 to 11 in the primary schools. In 1972, 9,128 white children were included in the sample. Data for this study were obtained in a follow-up study conducted in 1973. At this time, 7,851 (86%) of the original sample was available.

Data were collected via a self-administered questionnaire completed by the parent or guardian. Variables used for this report include:

- prevalence of respiratory symptoms or disease for each child over the past twelve months,
- type of cooking fuel used in the home,
- age of child,
- sex of child,
- socioeconomic status,
- latitude of area, and
- urban/rural location.

Complete data were available for 5,758 children of which 3,204 lived in homes with electric cooking and 2,554 lived in gas homes. While the response rate for the original 1972 sample is not given, only 63% of those eligible for 1973 were included in the analysis.

ANALYSIS METHODS: All analyses were done separately for boys and girls. Simple prevalences for each symptom or disease were compared for children in gas homes and children in electric homes. The authors then conducted more sophisticated analyses since they recognized that conditions other than cooking fuel might affect the prevalences.

An original categorical dependent variable was constructed from responses to five respiratory disease categories (asthmatics were excluded):

- Category 1: no symptom or disease
- Category 2: one symptom or disease
- Category 3: two symptoms or diseases
- Category 4: three or more symptoms or diseases.

Dichotomous independent variables were formed on the basis of:

- social class (upper vs. lower)
- age (below 8 years vs. 8 years or older)
- type of cooking fuel.

A log-linear model analysis was used to determine the effect of each of these variables on the response category.

A second analysis using the same methodology was performed by (i) combining response Categories 3 and 4, and (ii) adding a three-level variable to measure latitude. This analysis was conducted separately for boys/girls and urban/rural classifications, giving four separate analyses.

A third analysis used two response categories (Categories 2,3, and 4) were combined as the dependent variable with social class, age, area (28 groups) and cooking fuels as independent variables. Logit analysis was used to estimate effects of the independent variables.

Other independent variables were also studied: number of siblings, overcrowding, heating fuels, atmospheric conditions. How these were incorporated is not described.

RESULTS: Most of the analyses supported the contention that the prevalence of respiratory disease is higher in homes with gas cooking fuel, even after accounting for other factors that may also affect prevalence of respiratory illness. However, the results are not always consistent. Magnitudes of the "effect" are not given, only the level of statistical significance, and valid comparison of the different analyses cannot be undertaken.

In the first analysis, age, social class, and cooking fuels were all significantly correlated with illness for both boys and girls. The second set of analyses showed some anomalies. "For rural areas there was some evidence, confined to girls, that there was more illness in southern England. For urban areas, on the other hand, the proportion of children in the more severe categories was highest in northern England and lowest in the South. . ."

While all these analyses showed a higher prevalence of respiratory illness in gas homes, the association was significant only for girls in urban areas. The logit analysis showeda significant effect of gas cooking in girls but not for boys.

COMMENTS:

Incomplete and Missing Data	As mentioned earlier, about 65% of the eligible respondents were included in the analysis. How this affects the results cannot be determined. The effect would be important, however, only if the relationships between the study variables were importantly different among those with incomplete or missing data.
Accuracy of Data	Using recall data on respiratory illness may introduce errors that make the results less precise. The direction of the results will not be affected, however, unless the recall errors vary systematically for different levels of the predictor variables.
Definition of Response Variable	All of the symptoms and diseases were given equal weight based simply on whether or not they had occurred. Variations in the severity of the diseases/symptoms was not considered. Choosing a different response variable could either strengthen or weaken the general effects shown here.
Analysis Methods	Assumptions for the validity of the analysis methods most probably <u>are not</u> satisfied. As a result, results of all significance tests must be viewed with extreme caution. Valid use of GLIM requires that observations be made on a simple random sample from the population of interest. The sample design used here is a stratified multistage cluster sample with unequal selection probabilities. Observations made in the same geographic area, same school, or in the same home are not likely to be independent of each other. Both the response and explanatory variables are likely to exhibit strong "cluster effects." In addition, weights should be applied to account for unequal selection probabilities. The effect of this on the analyses is that the results are not as precise as they appear to be. The sample of 5,758 children probably does not contain 5,758 independent pieces of information. Significant results may be, in fact, insignificant if the analysis were done correctly. It is unlikely that the direction of the results is misleading, but the significance tests should be viewed quite cautiously.

EFFECT OF OMITTED VARIABLES

No measures were given that allow us to assess how well the included variables explained the variability in prevalence of respiratory symptoms/diseases. The inconsistencies in the second set of analyses lead us to conjecture that some other unmeasured variables are affecting the responses. One possible variable, mentioned in the paper, is family smoking habits. We note, however, that for any such unmeasured variable to affect the results, it must satisfy two criteria:

(i) its distribution must be different for gas-cooking homes than for electric-cooking homes; and

(ii) it must be associated with respiratory illness.

SUMMARY

Results given in this paper provide some support for a higher prevalence of respiratory illness among children in gas-cooking homes. The effect is not always strong and all significance tests may be invalid because of an inappropriate analysis.

None of the results, even with a valid analysis, can support a direct causal relationship between gas cooking and respiratory illness. An observational study, such as this one, can only provide information on associations and not causality.

AUTHOR: Melia, R.J.W., C. Florey, S. Chinn

TITLE: The Relation Between Respiratory Illness in Primary Schoolchildren And The Use of Gas for Cooking, 1-Results from A National Survey.

SOURCE: International Journal of Epidemiology 8: 333-338, 1979.

DATA COLLECTION: Two sets of data were analyzed for this report. The first is a cross-sectional sample of school children aged 5 to 11 years collected in 1977. The sample design and data collection methods are virtually identical to those described by Melia, et al (1977). The analysis was carried out with data from 4,827 of 7,794 eligible respondents. The overall response rate was not given.

Except for the inclusion of the number of smokers in the home, and apparently height and weight, the same variables were measured as in 1973. The authors state that the average height, weight, and age of the analyzed and unanalyzed children are not significantly different from each other.

The second set of data was obtained from further follow-up of the sample children included in the 1973 effort. The anlysis includes only those children who were followed for at least one year and whose cooking fuel did not change. Of the 5,758 children with complete data in 1973,

2,408 had data for five years (age 6-6.4 in 1973)
537 had data for four years (age 6.5-7.4 in 1973)
502 had data for three years (age 7.4-8.4 in 1973)
578 had data for two years (age 8.5-9.4 in 1973)
791 had data for one year (age 9.5-10.9 in 1973).

The remaining 942 were lost or had incomplete data.

ANALYSIS METHODS:

1977 Cross-sectional Data: Analysis methods are very similar to those reported for the 1973 cross-sectional data. A binary response variable was used throughout.

Category 1: No respiratory symptoms/diseases

Category 2: At least one respiratory symptom/disease

Crude prevalence rates were calculated for each of the six symptoms/diseases and for the summary variable, according to sex and type of cooking fuel (gas or electric).

Children were stratified into eight groups according to age, sex, and social class. Within each group, the proportion exhibiting respiratory symptoms was calculated separately for gas and electric cooking homes. The relative risk of having gas cooking was calculated for each of the eight groups. Overall relative risks for boys and girls were found by taking a weighted average across the other groups.

Log-linear model analysis was used to estimate the effects of:

- smokers
- age
- social-class
- cooking fuels
- latitude.

This analysis was conducted separately for each sex x urban/rural group.

Other explanatory variables were considered:

- overcrowding
- heating fuel
- outdoor pollution
- gas water heaters
- pilot lights.

Longitudinal Data

Five cohorts were defined on the basis of age in 1973. Four of the cohorts had data for at least two years. Crude relative risks were calculated for each cohort for each year (separately for boys and girls) and presented in a graph.

RESULTS:

Cross-sectional Analysis

Crude prevalence rates of respiratory symptoms were higher for both sexes, in homes with gas cooking. Prevalences were lower, overall, than in 1973.

After stratifying on age, sex, and social classes, the relative risk of respiratory illness for living in gas cooking homes vs. living in electric homes was 1.25 for boys and 1.19 for girls. Both were determined to be significantly greater than 1.0.

The number of cigarette smokers was found to be correlated with use of gas cooling in the manual, but not the non-manual social classes. Overall the prevalence of cigarette smokers was higher in the non-manual classes.

Some log-linear analyses included smoking, age, social class, and latitude as predictor variables. The association between gas cooking and respiratory illness was significant for both boys and girls in urban areas but not in rural areas. The effect of smoking was significant only in the rural areas.

When the analysis was extended to account for overcrowding heating fuel, and outdoor pollutants, the effect of gas gas cooking was significant for boys only.

A crude (unadjusted) association was found between respiratory illness and gas water heaters for girls only. When an extended model was used, the effect of gas water heaters was inconsistent across the cooking fuel and social class groups. The average effect was significant for girls, however.

Use of a pilot light on a gas cooker was associated with a positive but insignificant increase in illness.

Longitudinal Analysis — Only crude relative risks are given. They are usually greater than 1, but vary by sex and cohort. In the third cohort, girls have consistently higher relative risks, while boys dominate the fourth cohort.

COMMENTS: — All of the comments concerning the previous paper by Melia, et at., 1977 apply here. It is of particular importance to remember that all significance tests may be invalid because the necessary assumptions are not satisfied by the sample design.

Results Due to Chance — The authors' comment that certain anomalous results may be "due to chance" has no justification. The probability of "chance errors" in significance testing is controlled by the significance level. Each significant result has (essentially) the same probability of being in error. A more likely explanation is that other variables, not included in the analysis, are affecting the outcome.

SUMMARY: — As in the analysis of the 1973 data, the 1977 cross-sectional data showed, overall, that prevalence of respiratory illnesses in children is associated with gas cooking fuel. The actual significance level of the findings cannot be determined. Some inconsistent effects were found that lead to the conclusion that other variables should be included in the analysis. Again, these indirect correlations do not provide strong evidence that using gas fuel for cooking causes more respiratory illness.

AUTHOR: Florey, C. duV., R. Melia, S. Chinn, B. Goldstein, A. Brooks, H. John, I. Craighead, X. Webster

TITLE: The Relation Between Respiratory Illness in Primary School-children and the Use of Gas for Cooking, III-Nitrogen Dioxide, Respiratory Illness and Lung Infection

SOURCE: International Journal of Epidemiology. 8:347-353, 1979

DATA COLLECTION: Data used in this report are described under primary data in the review of the second paper in this series. Complete data from the questionnaire, NO_2 levels and lung capacity measurements were obtained for 60% of the 808 children. Three measures of lung capacity were included in these analyses:

PEFR = peak expiratory flow rate

$FEV_{.75}$ = forced expiratory volume at .75 seconds

MMF = mean flow over the mid-half of the forced vital capacity

The methodology for obtaining these measures is described in the paper.

DATA ANALYSIS AND RESULTS Dependent variables consisted either of the lung capacity measures or a binary variable indicating presence or absence of respiratory symptoms/diseases. Independent variables were either type of cooking fuel or NO_2 level in conjunction with other covariates such as age, sex, social class, etc.

A logistic regression was done using presence or absence of respiratory illness as the dependent variable. Age, sex, social class, presence of a smoker, and cooking fuel were the predictor variables. Age, sex, and social class were insignificant while gas cooking fuel and presence of a smoker were both correlated with the occurrence of respiratory illness. Deleting social class as a variable increased the sample size from 422 to 526, but apparently weakened the relationship between gas fuel and respiratory illness.

Complete data on respiratory illness and bedroom NO_2 concentrations were available for 103 children in gas cooking homes. Respiratory illness was associated with bedroom NO_2 both before and after accounting for age, sex, social class, and presence of smokers. No relationship was found between kitchen levels of NO_2 and respiratory illness for any family members.

Linear regression was used to analyze the association between lung capacity and NO_2 levels using height, age, and sex as covariates. No significant relationships were found. In a separate analysis slightly higher values of PEFR and MMF were found for girls in gas cooking homes.

COMMENTS: Invalidity of the significance tests because of correlations among the observations is a problem. The children in the sample came from ten primary schools in the study area. It is quite likely that occurrences of respiratory illnesses are correlated among children in the same school. Therefore, the results may be less significant than they seem.

Lack of independence between observations may also affect the regression analyses, but two other aspects of the regressions also deserve comment. The validity of the normality assumptions does not appear to have been tested. Transformations of the original data may be required. The figure in the paper shows a few outlying observations that may have a disproportionate effect on the estimated coefficients. Procedures for testing normality and assessing the effects of outliers are well-developed and should be routinely applied.

Another assumption that is required for linear regression is that the predictor variables, particularly the NO_2 concentration, are measured without error. This assumption may be severely violated for these data. When this assumption is violated, positive regression coefficients tend to be closer to zero than they should be. Therefore, the relationship between lung capacity and NO_2 may actually be stronger than it appears. More analysis, using transformations and an errors-in-variables regression model, is needed.

The authors' comment (top of p. 349) concerning the role of sample size and the chance of identifying relationships does not appear to be valid. This has no effect on the remainder of the paper, however.

The high rate of missing data affects the validity of the results only if the relationship between respiratory disease and the other factors is strongly different for the unanalyzed children.

As the authors note, the presence of other variables that may also affect respiratory disease must be considered in interpreting the results.

SUMMARY:

The authors found a small relationship between respiratory illness in children and NO_2 concentrations in the bedroom. No relationships were found between lung capacity and NO_2 after controlling for other variables. Lung capacity did differ slightly between girls with gas and electric cooking stoves.

Both the regression analyses and the log-linear logit analyses may suffer because the assumptions for their validity are not satisfied. Correct analyses would not change the direction of the results but would change the p-values for some of the tests.

AUTHOR: Goldstein, B.D., R. Melia, S. Chinn, C. Florey, D. Clark, H. John

TITLE: The Relation Between Respiratory Illness In Primary Schoolchildren And The Use Of Gas For Cooking, 11-Facts Affecting Nitrogen Dioxide Levels In the Home.

SOURCE: International Journal of Epidemiology, 8:339-345, 1979.

DATA COLLECTION:

Primary Data

The sample was defined as all 808 children, 6 to 7 years old, living in a 4 km^2 area in Middlesborough, England, and attending the ten local primary schools in February 1978. These children lived in 769 homes.

Two NO_2 samplers were left for a week in the kitchen of each home, and a third was placed in the child's bedroom in 25% of the homes. Data on respiratory illness, home environment, social class, etc., were obtained from a self-administered questionnaire filled out by the child's mother. Lung function and other physical measurements were obtained in the schools.

The NO_2 samplers were reported to be accurate to within $\pm$ 10%. An effort was madeto place the NO_2 samplers in a uniform location with respect to the cooking stove. Two measurements were obtained in 507 kitchens and a single reading in nine additional kitchens. The average of the duplicate readings was used in analysis. One home was excluded because the cooking fuel was camping gas. The homes included 428 with gas cookers and 87 with electric. NO_2 levels were measured in the child's bedroom in 107 homes with gas cookers. Complete data were obtained for 420 gas cooking homes.

Samplers were also placed in the 76 outdoor locations.

Follow-up Data

The 32 gas cooking homes with highest NO_2 readings were revisited to obtain additional data on:

- number of nobs, pilots, lights, open grills, and oven on the gas cooker;
- kitchen size and ventilation;
- average daily number of meals eaten;
- other gas applicances;
- other uses of the cooker.

Each of these homes was paired with a gas cooking home with low NO_2 on the basis of:

- pilot light,
- gas heating,
- smokers (0 or 1 vs. 2 or more)
- household size (< 4 vs. $\geq$ 4)
- kitchen area (< $8m^2$ vs. $\geq 8m^2$)

These homes were also revisited to obtain the additional data. Complete follow-up data were obtained for 29 of the pairs.

ANALYSIS AND RESULTS:

Distribution of NO_2 Concentrations

Histograms showed highly skewed distributions of NO_2 concentrations for kitchens with gas cookers, kitchens with electric cookers, and bedrooms in gas cooking homes. Mean concentration for gas cooking kitchens was 112.2 ppb, for electric kitchens 18.0 ppb and 30.5 ppb for bedrooms in gas cooking homes. Correlation between kitchen and bedroom levels was .33 for gas homes and .52 for electric homes.

Regression analysis was done to explain the variation in kitchen NO_2 concentrations for 420 gas cooking homes. The following independent variables were used:

Presence of flueless gas fire	(negative effect)
Presence of one or more pilot lights	(positive effect)
Presence of gas fires for main heating	(insignificant)
Presence of paraffin heaters for main heating	(insignificant)
Number of people in home without paraffin heating	(positive effect)
Number of people in home with paraffin heating	(positive effect)
Number of cigarette smokers	(positive effect)
Kitchen area	(insignificant)

Several other variables describing gas water heaters and main heating were eliminated after preliminary analyses. The authors were puzzled by the negative effect of a flueless gas fire. All the variables combined explained 11% of the observed variability on NO_2 concentrations.

Analysis of the follow-up data was undertaken on 41 items in an attempt to determine if any of these contribute uniquely to the very high NO_2 concentrations. Only two variables, total number of meals consumed and use of cooker for space heating or clothes drying, were significant.

Outdoor levels of NO_2 were similar to those found in electric kitchens and lower than in most gas cooking homes.

COMMENTS:

A single glance at the histograms confirms that NO_2 levels are higher in gas cooking kitchens. The highly skewed distributions indicate that the correlation and regression analyses are inappropriate but probably not misleading. An approximately normal distribution is required for validity of these tests. The data should have been transformed, possibly a logarithmic or square root transformation, before undertaking any further analysis or testing. While the direction and substance of the results probably would not change, the precision and validity would be improved.

No mention is made of attempting to include non-linear models or interactions in the regression analysis. The procedure used to choose the factors included in Table 1 of the report is not documented. The appropriateness of the regression model cannot be evaluated without the use of residual plots, tests for outliers, and results from alternative regressions.

SUMMARY:

NO_2 levels are higher in gas cooking kitchens. Five variables were identified that appear to be correlated with NO_2. The regression of NO_2 level on other variables yielded an R^2 of 11% indicating that variables other than those included play an important role in determining NO_2 concentration. An alternative explanation is that a lot of unexplained measurement error exists in the NO_2 data.

Validity of correlation and regression procedures would be improved by transforming the data. The regression methodology is poorly documented.

AUTHOR: Speizer, F.E., B. Ferris, Jr., Y. Bishop, and J. Spengler

TITLE: Respiratory Disease Rates and Pulmonary Function in Children Associated With NO_2 Exposure.

SOURCE: American Review of Respiratory Disease 121: 3-10, 1980. The methodology of the study is reported by B.G. Ferris, Jr., et. al. "Effects of Sulfur Oxides and Respirable Particles on Human Health," Am. Rev. Resp. Dis. 120: 767-779, 1979.

DATA COLLECTION: Data was obtained for school children in six cities concerning respiratory diseases, type of cooking fuel, and other household information. A second data collection activity involved measuring indoor-outdoor levels of NO_2 at a sample of selected homes. Each component will be described in more detail in subsequent sections.

Six cities were selected purposely for inclusion in this long-range prospective study. The following criteria were considered in the selection.

- availability of historical air pollution data
- stable population
- population of approximately 50,000 persons
- no large confounding occupational group
- few sources of different types of air pollution
- homogenous ethnic mix
- cooperation of local health and education officials.

The six cities selected are:

- Watertown, Massachusetts
- Kingston-Harriman, Tennessee
- St. Louis, Missouri (southern end)
- Steubenville, Ohio
- Portage, Wisconsin
- Topeka, Kansas

Historical pollution levels, as measured by sulfur dioxide, total suspended particulate, and suspended sulfates, vary widely across the six cities with Portage being the least polluted and Steubenville the most polluted.

Children were selected for participation through the local school systems (including parochial schools). In four cities, the initial sample included all first and second-grade children. All children in grades 1-4 were selected in Portage in order to achieve an adequate sample size. In Topeka, which was larger, a random sample at somewhat more than half the schools are being followed. The response rate was greater than 95% for all schools. No schools refused to participate.

All schools were revisited annually, but the first visits were spread over a three year period. New first graders were added to the sample on the first two revisits if the sample size for that community was less than 1,500.

The data analyzed in this report come from 12 cohorts in six cities. Two cities had been visited three times. During each visit new first graders were added. This gives three cohorts per city. Two cities had been surveyed twice, each yielding 2 cohorts. The remaining two had been surveyed only once. Altogether 9,280 children participated in the initial survey. The data analyzed here pertain to 8,120 white children between the ages of 6 and 10 at the initial visit. None of the follow-up data are included in this analysis.

Variables measured for each child on the intiial visit include:

- type of home-cooking and home-heating fuel,
- presence or absence of air conditioning,
- presence or absence of adult smokers in the household,
- living conditions,
- parent's occupation,
- family composition,
- previous respiratory illnesses of the child and of the parents,
- forced vital capacity (FVC),

- forced expiratory volume in 1 second (FEV_1),
- height,
- weight, and
- age.

All data except the physical measurements were obtained from a questionnaire filled out by the child's parent(s).

Data on NO_2 exposure were obtained from a small sample of homes in each community. The homes were sampled for 24 hours every sixth day. Data collected between May 1977 through April 1978 were used in these analyses. The variable analyzed is 24-hour integrated average NO_2 level measured in an "activity" room, not a kitchen or bedroom. Simultaneous outdoor measurements were taken for each home. From five to eleven homes in each city participated in the air quality monitoring. They were chosen to be "representative of the kinds of living patterns found in each community."

ANALYSIS OF EXPOSURE DATA:

It is hard to ascertain how the air pollution data were analyzed. On p.4, at the end of "Methods" section, the use of analysis of variance is mentioned. Yet the only results presented are a table of geometric means of the integrated 24-hour values. Means are given separately for each city, type of cooking fuel, and indoor-outdoor site.

Use of the geometric mean as a descriptive statistic is appropriate for highly skewed distributions as extremely large observations are given less weight. While the observed distributions are not displayed, many sets of air pollution measurements result in skewed distributions.

The averages were apparently calculated by including the data from all homes with a given cooking fuel and all days of measurement for a city. The results show that, except for one city, indoor NO_2 levels are greater than outdoor levels for homes with gas stoves. The reverse holds for electric cooking homes, again with one anomalous city. These trends hold across all cities when comparing the 95th percentile of the NO_2 distributions.

Very few homes are included in the sample. Most of the data come from repeated measurements on the same home. Portage and Kingston-Harriman each had eight electric-cooking homes. This is the maximum. Results from gas-cooking homes in Topeka are based on a single home.

A single continuous monitoring of a single unvented kitchen showed NO_2 concentrations ranging from 1100 ug/m^3 (a single short-lived peak) down to 100-200 ug/m^3.

ANALYSIS OF DISEASE RATES:

Responses to three Yes-No questions were analyzed.

- history of bronchitis diagnosed by a physician,
- history of serious respiratory illness before age two, and
- history of respiratory illness in the last year.

Answers to these questions were obtained from the questionnaire filled out by the child's parent(s).

Log-linear model and methodology was used to evaluate the association between presence of disease and type of cooking fuel after controlling for other variables. 94% of the homes could be unambigously classified as either gas or electric. Across cities they were divided almost evenly between the two, but the percent of homes with gas cooking ranged from 82.2% down to 4.6% across the six cities.

It appears that the final results were based on an analysis that included parental smoking, social class (based on occupation and education of parents), type of cooking fuel, sex of child, and city-cohort as independent variables. It is not clear from the paper whether these variables were all considered simultaneously, whether certain subgroups were analyzed separately, or whether some kind of stepwise procedure was used.

The primary finding is that in a multivariate analysis that included parental smoking and social class, "the effect of the type of cooking stove had a significant association with respiratory disease before age 2, but not with the other 2 reported diseases." Disease rates adjusted for smoking and social class were presented separately for each cooking fuel, city-cohort, and sex. In each case the adjusted rate was higher for gas cooking homes than for electric cooking homes.

ANALYSIS OF PULMONARY FUNCTION:

For the first step of this analysis, an expected lung function was calculated for each child for the variables FVC and FEV_1. The expected values were calculated by regressing FVC and FEV_1, on height, separately for each age group. Data from two cities only, obtained during the third year of the study, were used in the regression.

For each child, a residual deviation from his/her expected value was calculated and used as input into further analysis. Apparently, sex of the child was not included as an adjustment value. The residual deviation should be orthogonal to height and age when this procedure is used.

The residual deviations were then subjected to further analysis to ascertain if other variables could account for any of the remaining variability. Socio-economic status was dropped from the analysis after a preliminary regression showed no association with lung function. The first finding was the existence of the city-cohort differences found after adjusting for height and age. Other independent variables tested were home heating fuel, cooking fuel, air conditioning and parental smoking. It is not possible to tell whether these variables were examined simultaneously or one-at-a-time, but all comparisons were adjusted for city-cohort effects.

Levels of both FEV_1 and FVC were significantly lower for children from gas-cooking homes. Home heating fuel had a significant effect on FEV_1 with the lowest values in oil-heated homes and the highest values in electric homes. Presence of air conditioning was not related to either variable, while parental smoking had a significant effect on FVC. The strange thing is that children in smoking homes had a higher average than children in nonsmoking homes. No explanation was offered for this finding.

It is difficult to assess accurately the magnitude of the cooking fuel effect. The difference between the averages of electric and gas-cooking homes is 16 ml and 18 ml for FEV_1 and FVC, respectively, but no overall average is given, nor do we know what these differences mean in terms of disease.

<u>COMMENTS</u>:

- Indoor-Outdoor NO_2 Measurements

  An important question to address with these data is: how many gas-cooking homes have substantially higher NO_2 concentrations and what conditions are associated with these higher levels? The analysis presented here examines the average NO_2 levels across homes, but no information is given with which to assess the consistency of these findings for individual homes. It seems that indoor NO_2 levels might be affected by many factors such as ventiliation, family composition, life style, location of home, etc., as well as type of cooking stove.

- Health Data

  Except for one possible drawback, the log-linear model is an appropriate analysis methodology for these data. The brief description of its application makes it impossible to evaluate how the methodology was applied. The results presented in Figure 3 are convincing because of their consistency, but the consistency could be an artifact of the analysis if important interactions were ignored. For some reason, only 10 of the 12 city-cohorts are included in Figure 3.

  While city-to-city differences in disease rates are to be expected, the dramatic difference between the two St. Louis cohorts is anomalous. It seems strange that parental recall of respiratory illness before age two would vary so dramatically for two different cohorts who entered the study only a year apart.

  The purpose of using control variables is to allow for comparisons of disease rates to be made on groups of children that are as similar as possible. Since the children were studied in their schools and school districts are more demographically homogenous than cities, it seems that accounting for school-to-school differences might be useful. School might serve as a surrogate for income, type of home, local air quality, or other variables that could not be explicitly controlled in the analysis. Quite possibly the overall direction of the results would not change, but the consistency of the result could be determined.

- Pulmonary Function

  Again, the description of the analysis is not complete enough for a full evaluation, but the choice of methods appears appropriate. The two variables FVC and FEV_1 were ajusted for height separately for each age group. Data from only two of the cities were used to develop the equation used to make the adjustment. If the relationship between lung function and height is approximately the same for all cities, this may be an appropriate adjustment procedure. Perhaps earlier studies have shown little regional variation in this relationship. Apparently the sex of the child was not considered in the adjustment. The rationale of "adjusting" for important covariates before analyzing the independents variables of interest is sound.

While the apparent negative correlation between gas-cooking and lung function is emphasized in the results, the apparent positive association of parental smoking and FVC also deserves attention. This unanticipated finding indicates that something may be wrong with the model, with the data, or with the analysis. Possibly an important control variable is missing, or there were severe reporting errors in the smoking data, or errors in the data entry or analysis. As mentioned earlier, factors that vary from school-to-school may be associated with variability in lung function.

SUMMARY: This report on the Harvard Six-City Study contains results on indoor NO_2 levels, and the association of gas cooking with respiratory disease and pulmonary function. While higher NO_2 levels were found in gas-cooking homes, only a small number of homes was studied and variability between homes was not examined.

Appropriate statistical methodology was used to analyze the health and pulmonary function data, but the description is too brief to evaluate fully the methodology. An anomalous positive association between parental smoking and pulmonary function weakens the credibility of the results, although the association between reported respiratory illness before age two and gas-cooking appears real. It seems that school-to-school variability might be important in explaining both disease and lung function variability, but this was not considered.

APPENDIX III

AIR INFILTRATION

ANNOTATED BIBLIOGRAPHY OF SELECTED STUDIES

AUTHOR: American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE)

TITLE: 1977 Fundamentals

SOURCE: ASHRAE, Inc., New York, N.Y., 1977

SUMMARY: Chapter 21 on "Infiltration and Ventilation" describes the factors that influence infiltration and presents the two methods commonly utilized by design engineers to estimate infiltration rates in homes and other structures.

COMMENTS: This chapter is essentially the "bible" on the subject for design engineers. Nevertheless, the review of pertinent literature contained herein will demonstrate that the infiltration rate estimation methods provided by ASHRAE have a number of important deficiencies.

AUTHOR: Bahnfleth, D.R.; T.D. Moseley; W.S. Harris

TITLE: Measurement of Infiltration in Two Residences, Part I: Technique and Measured Infiltration

SOURCE: ASHRAE Transactions, 63, 439-452, 1957

SUBJECT: The authors describe two research houses, their method of determining air infiltration rates, and the results of a series of tests to measure infiltration rates under varying wind and temperature conditions.

METHODOLOGY: One house was a 2-story building with full basement considered typical of small well-built American homes. Construction was brick veneer on wood frame. The other was a one-story frame structure with a full basement. Infiltration rates were measured using helium as a tracer gas.

RESULTS: With the indoor-outdoor temperature difference ranging from -9 to 47°F, and the average wind velocity ranging from 4 to 13 mph, the infiltration rates (whole house) ranged from 0.16 to 0.43 air changes per hour (ACPH) in the first house. Over a temperature difference range of -17.6 to 70.0°F, and a wind velocity range of 3 to 15 mph, the infiltration rates in the second house ranged from 0.26 to 0.80 ACPH. Windows and doors were generally kept closed in all tests. Both houses were well-built and had weather-stripping where necessary. The second house had storm windows and doors installed during winter tests.

COMMENTS: None.

AUTHOR: Bahnfleth, D.R.; T.D. Moseley; W.S. Harris

TITLE: Measurement of Infiltration in Two Residences; Part II: A Comparison of Variables Affecting Infiltration

SOURCE: ASHRAE Transactions, 63, 453-476, 1957

SUBJECT: Using the data presented in Part I of the paper, the authors attempt to define the effect of wind and temperature forces on infiltration rates.

METHODOLOGY: Graphical techniques were used to "correct" the measured infiltration rates to wind conditions of 0, 7.5, and 15 mph, and indoor-outdoor temperature differences of 0, 35, and 70°F. Results were compared with predictions made using ASHRAE design methods. Differences in the behavior of the two houses were explained in terms of construction and heating system characteristics.

RESULTS: There was good agreement between measured and calculated infiltration rates. The good agreement was a result of over-estimating the effect of wind forces and neglecting the effect of temperature difference forces when using the ASHRAE crack method of estimation. It may not have occurred if the houses were located in other climates.

At zero wind velocity and temperature difference, the infiltration rates for the two houses were respectively 0.12 and 0.19 ACPH. The authors attributed these results to diffusion of helium through the walls, ceilings and floors.

For the first house (2-story), it was determined that a change of 4°in temperature difference was equivalent in effect (a change of 0.013 ACPH) to a 1 mph change in wind velocity. Due to the effect of the chimney, winter infiltration rates for a given wind velocity and temperature difference were greater than summer rates under similar conditions.

In the second house (1-story), each mph increase in wind speed caused the infiltration rate to increase by 0.012 ACPH, while each degree F of temperature difference caused a change of 0.0066 ACPH.

Insufficient data were gathered to fully consider the effect of wind direction. The authors noted, however, that the first house, located on a typical city site surrounded by large trees and houses, had a considerably lower infiltration rate than the second house, which was on a relatively open site. Indeed, even the presence of leaves on trees were seen to affect results.

COMMENTS: This is an excellent early paper that formed the basis for much work that followed. It has a few deficiencies in the way the authors use and interpret data, but this is understandable given the pioneering nature of some of this work.

AUTHOR: Blomsterberg, A.K.; D.T. Harrje

TITLE: Evaluating Air Infiltration Energy Losses

SOURCE: ASHRAE Journal, 25-32, May, 1979

SUBJECT: The authors present a procedure for estimating infiltration rates in residences and compare its results to measured rates. The effect of sealing various leakage sources is investigated.

METHODOLOGY: A tracer gas dilution method using sulfur hexafluoride was used to measure infiltration rates in houses subject to normal environmental conditions. A fan installed in an external doorway was utilized to measure rates when indoor-outdoor pressure differences were varied over a range of pressures up to 50 Pa.

RESULTS: It is noted that various models overestimate infiltration rates due to their inability to properly quantify and account for a number of factors. Important factors identified included the protection afforded by terrain, differences in wind pressure distribution due to building shape, the location of openings with respect to the wind, internal bypasses such as shafts and the like, and internal flow resistance.

The average infiltration rate measured in six homes before retrofitting to reduce leaks was 0.7 air changes per hour (ACPH). After retrofitting, the average fell to 0.4 ACPH. The indoor-outdoor temperature difference during these tests was 17°C. The wind velocity was 4 m/s.

The location of openings was shown to be important in a series of experiments using a test-box with specified openings. The highest infiltration rate was achieved with openings low on the windward side and high on the leeward side. The lowest rate was achieved with all openings on the windward side. The authors conclude that more research is needed to better understand such factors as the microclimate and how openings are distributed around a building.

COMMENTS: The authors' conclusion and demonstration that the location of openings is important can partially explain the difficulties other researchers have had in obtaining consistent results when wind directions change (or are ignored) but all other factors remain fairly constant.

AUTHOR: Briggs, T.M.; M. Overstreet; A. Kothari; T.W. Devitt

TITLE: Air Pollution Considerations in Residential Planning; Volume I: Manual; Volume II: Backup Report

SOURCE: EPA Report No. EPA-450/3-74-046-a and -b; NTIS Report No. PB-240-997-and-998, July 1974.

SUBJECT: A procedure is presented for determining the air pollution exposure of residential developments. The results are used in a procedure for converting total outdoor pollutant concentrations to indoor levels as a function of building structural characteristics. Recommended design practices are presented to aid a planner in minimizing the impact of air pollution on residents of a development.

METHODOLOGY: This is essentially a paper study based on a literature review. Air dispersion models, a model of building penetration by outdoor contaminants and some limited data on internally generated contaminants are used to develop a workbook type procedure for determining indoor pollutant concentrations.

RESULTS: The authors very sketchily describe the model they used to predict indoor pollutant concentrations. The model generally shows the correct relationship between indoor and outdoor pollutant levels.

COMMENTS: Indoor pollutant concentrations have recently been determined to be a sensitive function of a number of complex factors. This 1974 report clearly does not adequately consider variations in infiltration rates and in generation rates of internally generated contaminants. The results of the model may therefore be inaccurate.

AUTHOR: Brundrett, G.W.

TITLE: Ventilation: A Behavioral Approach

SOURCE: International Journal of Energy Research, 1 (4), 289-298, 1977

SUBJECT: This paper reports upon behavioral studies of the window-opening habits of families in 123 homes in England.

METHODOLOGY: The researchers observed the window-openings in the houses over a period of approximately 1 year. In addition, they interviewed householders to obtain views on window opening and details about families.

RESULTS: More than three-quarters of the test population was under 34 years of age. It was common to find open windows throughout the year with the number of open windows being most strongly linked to external humidity levels in winter and mean temperatures in summer. The most popular rooms to have open windows were bedrooms. The windows in other rooms were open much less often, but with the exception of the kitchen where windows were often open even in the coldest weather. Houses where the housewife is at home are much more likely to have an open window. Also more likely to have open windows are larger families.

COMMENTS: What is surprising is the number of homes with open windows even in the coldest months. The survey showed, at the minimum, that 1 out of 4 homes had an open window on the average during December. From May to September, the average number of open windows in each house generally exceeded 1.0, with averages as high as 2.89 being recorded.

AUTHOR: Burch, D.M.; C.M. Hunt

TITLE: Retrofitting an Existing Wood-Frame Residence to Reduce its Heating and Cooling Energy Requirements.

SOURCE: ASHRAE Transactions 84, 176-196, 1978

SUBJECT: A wood-frame residence built in the early 1950's and having only limited insulation in the attic was retrofitted in three stages to reduce its energy requirements for heating and cooling. The house was extensively instrumented to evaluate energy savings and changes in air infiltration rates.

METHODOLOGY: Sulfur hexafluoride tracer gas was used in conjunction with a semi-automated sampling system and a gas chromatograph with an electron-capture detector to measure infiltration rates. These rates were measured before and after each of three phases of retrofit.

The first stage of retrofit involved reduction of air leaks through use of caulking compounds, weatherstripping, installation of a spring-activated damper in the kitchen exhaust system, and repair of a fireplace damper. In addition, the oil-fired furnace was replaced with a air-to-air heat-pump system connected to the existing air distribution system. The second stage involved the addition of wood-sash storm windows. The final stage involved application of insulation to the walls, ceiling, and floor.

RESULTS: Infiltration rate data were fit to equations using least-squares procedures. The equation for the test house before modification predicted a winter infiltration rate of 0.5 air changes per hour (ACPH) at a indoor-outdoor temperature difference of 35°F and a wind speed of 7 mph, thus indicating that the house in its original state had low infiltration rates. This was said to be due to good construction and good weatherstripping around the doors and windows.

The winter rates dropped by an average of 0.08 ACPH after the first stage of retrofit, which is not much larger than the normal statistical variation. The authors note that effects due to installation of the heat pump may have partially offset measures to reduce air leaks. After the second stage, the infiltration rates were found to be 0.04 ACPH higher than the pre-retrofit values on average, but this increase was less than the normal statistical variation. The third stage resulted in an increase on the order of 0.13 ACPH over pre-retrofit values at a temperature difference of 30°F and a wind speed of 5 mph. This increase was attributed to the finding that the addition of insulation resulted in an increase in temperature difference between the living space and the attic above and crawl space below.

Measured summer infiltration rates were predominantly in the range of 0.2 to 0.4 ACPH with very little difference between pre- and post - retrofit data. They averaged about half of typical winter values.

COMMENTS: The results as given suggest that there may be a practical limit beyond which measures to reduce air leakage are ineffective. It is noteworthy that the house in its original condition had low infiltration rates, and it is unfortunate that the installation of the heat pump may have masked the true effects of the air leakage reduction measures.

AUTHOR: Caffey, G.E.

TITLE: Residential Air Infiltration

SOURCE: ASHRAE Transactions, 85, 41-57, 1979

SUBJECT: Air leakage measurements were carried out in 50 homes to determine typical rates, to identify sources of leakage, and to assess the effectiveness of sealing techniques.

METHODOLOGY: An exhaust fan was mounted in a window of each house to simulate indoor-outdoor pressure differences due to external wind forces. Leakage paths identified were plugged by various techniques to judge their effectiveness. Infiltration rates on an hourly air change basis were computed by simply dividing the experimental results by 4, this being the average divisor determined as necessary through various experiments.

The claim was made that results agreed within 15% of rates measured with a tracer gas technqiue, with the tracer gas technique always providing the lower value. This latter observation was attributed to the fact that the tracer gas technique was applied during actual wind conditions of 0-12 mph while the exhaust fan technique always simulated a wind speed of 15 mph.

RESULTS: Twelve major areas of leakage were identified, with the most important being the bottom plate or base board area of the exterior wall (25% of total infiltration). Leakage due to windows, doors and sliding glass doors contributed 19% to totals. It was found possible to caulk, tape and/or seal approximately 60% of the overall leakage of a home at a very reasonable cost.

At an indoor-outdoor pressure difference equivalent to a wind speed of 15 mph, the average infiltration rate determined for the 50 houses was 1.49 air changes per hour (ACPH). The overall range was 0.35 to 2.7 ACPH. The house with the lowest rate had exertior walls filled with urea-formaldehyde foam and exterior walls and ceilings innerlined with "polyplastic" film.

COMMENTS: The method by which infiltration rates were determined from leakage rate data is somewhat unique to this study and may or may not be fully appropriate. Of particular concern is an almost complete lack of attention to the effect of indoor-outdoor temperature differences on infiltration rates.

AUTHOR: Card, W.H.; A. Sallman; R.W. Graham; E.E. Drucker

TITLE: Air Leakage Measurement of Buildings by an Infrasonic Method

SOURCE: Final Report to the National Science Foundation under Grant No. ENG7523416, NTIS Report No. PB-282046, January 1978

SUMMARY: The authors investigate the feasibility of measuring the composite effective size of all the air-leakage passages of a building or part of a building by using an infrasonic method to yield flow versus pressure difference data. Sinusoidably varying volumetric flows between 0.05 and 5 Hz are generated by a motor-driven bellows-like source located inside the building under test. The resulting pressure variations are measured using a microphone-like sensor having an electronic signal processor. It was found that infrasonic and blower test results usually agree with a factor of three, but improved apparatus is expected to improve agreement in the future.

COMMENTS: The report simply describes a measurement technique that may someday provide an easily applied approach for determining the relative leakiness of buildings.

AUTHOR: Coblentz, C.W.; P.R. Achenbach

TITLE: Field Measurements of Air Infiltration in Ten Electrically-Heated Houses

SOURCE: ASHRAE Transactions, 69, 358-365, 1963

SUBJECT: The authors describe the results of experiments to determine the infiltration rates of 10 houses.

METHODOLOGY: Ten electrically-heated houses with storm sashes and varying construction characteristics were selected as being representive of a majority of residential construction. Five were practically new while 5 had ages ranging from 20 to 46 years. Infiltration rates were measured when all windows and doors were closed, using a helium tracer gas and an infiltration meter developed by the National Bureau of Standards. Indoor-outdoor temperature differences and outdoor wind conditions were measured simultaneously and recorded.

RESULTS: When the wind velocity ranged from 6 to 15 mph and the indoor-outdoor temperature difference ranged from 20 to 64°F, the infiltration rates for these houses ranged from 0.35 to 1.14 air changes per hour (ACPH). When all rates were crudely normalized to a 10 mph wind velocity and 40°F temperature difference, the range became 0.37 to 0.99 ACPH with an overall average of 0.64 ACPH. The rates were seen to differ not only from house-to-house but also from room-to-room in any given house. It is generally noted that the new houses had lower infiltration rates than the older homes. For the 5 houses in the former category, the normalized range was 0.37 to 0.66 ACPH with an average of 0.50; for the 5 older houses, the range was 0.62 to 0.99 ACPH with an average of 0.79. Conclusions cannot be drawn on the basis of age alone, however, because 4 of the 5 new homes were of stone or brick wall construction while 4 of the 5 older homes were of frame construction. The data also show that 2-story homes generally had higher infiltration rates than 1-story structures.

Use of the ASHRAE air change method of infiltration rate estimation gave answers ranging from 0.54 to 1.45 ACPH for these homes. Although the range was in fair agreement with observed rates, numerous inconsistencies were evident on a house-by-house basis.

COMMENTS: The experimental results provide a good indication of typical infiltration rates in electrically-heated homes of this era.

AUTHOR: Dick, J.B.; D.A. Thomas

TITLE: Ventilation Research in Occupied Houses

SOURCE: J. Inst. Heat. Vent. Eng., 19, 306-326, 1951

SUBJECT: This early paper from England is last in a series of four written by Dick between 1949 and 1951. The results are given of measurements of the air-change rates, environmental conditions, and the consequent rates of heat loss in occupied and unoccupied houses on two sites, one exposed and one sheltered. Observations of temperatures maintained and the window-opening habits of occupants are presented for a number of homes covered in a regional survey.

METHODOLOGY: Air-change rates were measured through the heating season using a tracer gas method and the results were correlated to observed window-opening habits of occupants. The heat losses from houses due to air changes were estimated using an equation that is presented. Wind pressures across the houses, air temperatures and wind velocities were monitored and also used in developing correlations and conclusions.

RESULTS: In the set of exposed houses studied, when all windows were closed, air change rates averaged about 2 per hour when the homes were heated but unoccupied. After occupation, with windows closed, the average dropped to about 1.5 air changes per hour (ACPH) due to actions of tenants in sealing the worst of badly fitting windows and in sealing certain "ventilators". About 0.87 ACPH were concluded to be due to inside-outside temperature differences, with the rest due to wind forces. The opening of single vents or windows was seen to increase the air change rate by 0.46 to 0.65 ACPH under mean wind conditions, and by 0.23 to 0.33 ACPH at zero wind conditions. Due to the window-opening habits of tenants, the actual mean air change rate during the experiment was about 2.5 ACPH. Not surprisingly, the number of open windows at the site was a function of wind speed and external air temperature.

The average air change rates in homes sheltered by nearby buildings and trees were found to be lower mostly due to shielding effects. The mean comparable to the 1.5 ACPH figure given above was 0.88 ACPH, even though it was shown that these homes would have higher rates than the first set described under similar conditions. Occupancy was seen to increase the mean rate by approximately 1.1 ACPH. Although the subject was not specifically studied, it is noted that the authors attribute about 0.5 ACPH due to air flow induced by heating appliances.

COMMENTS: This paper is obviously the result of an experimental program that was logically planned and executed to practically consider the major factors influencing air change rates in residences. Although there is some question whether the quantitative results are applicable to present-day conditions in the United States, it is clear that the findings are useful to an understanding of this subject area.

AUTHOR: Elkins, R.H.; C.E. Wensman

TITLE: Natural Ventilation of Modern Tightly Constructed Homes

SOURCE: Proceedings of the AGA/IGT Conference on Natural Gas Research and Technology, Chicago, February 28 - March 3, 1971

SUBJECT: This paper presents the results of a survey of the natural air infiltration rates in two identical modern homes (one gas-fueled and one all-electric) over a period of a year. The extent of variations in the rates and the factors that control these variations are discussed in light of ventilation needs.

METHODOLOGY: A tracer-gas decay technique was used to measure infiltration rates. Inside and outside environmental parameters, on-off times and energy consumptions of the major appliances, and family activities such as door openings and operation of vent fans were continually monitored and recorded by a computerized data acquisition system.

RESULTS: For these occupied one-story homes, wind velocity and direction were found to be the most important environmental factors influencing infiltration rates. Considerable variation in infiltration rates was observed on a day-to-day as well as hour-by-hour basis. The rates generally varied from 0.24 to 0.83 air changes per hour (ACPH) in the gas-fueled home and from 0.13 to 0.42 ACPH in the all-electric house. A rate as low as 0.066 ACPH was recorded during one afternoon in the all-electric home, however, and rates as high as 1.8 ACPH are noted in the paper for a short period of time during one test. The very low rate observed prompted the authors to conclude that construction technology has progressed to such a point in reducing heat loss that naturation infiltration can no longer be always relied upon to supply the minimum ventilation required for health and comfort in residential buildings.

COMMENTS: This is an excellent paper often referred to by researchers in this field. Its data for modern homes provides an accurate indication of actual infiltration rates in occupied residences.

AUTHOR: Gerrard, M.

TITLE: Measurement of Ventilation Rates with Radioactive Tracers

SOURCE: ASHRAE Journal, 10, 47-50, September 1968

SUBJECT: The author discusses the use of radioactive tracer gases for measuring ventilation rates.

METHODOLOGY: The paper is essentially a review of the literature regarding the use of radioactive tracer gases in prior ventilation rate studies.

RESULTS: Krypton-85 is proposed as the best choice for tracer use among the gases available due to the capability of Geiger-Muller counters to immediately measure small amounts in air.

COMMENTS: The findings of this paper are no longer valid. Sulfur hexafluoride has all the advantages of krypton - 85 with none of the disadvantages and is the current preferred choice among researchers.

AUTHOR: Goldschmidt, V.W.; D.R. Wilhelm

TITLE: Summertime Infiltration Rates in Mobile Homes

SOURCE: ASHRAE Transactions, 85, 840-850, 1979

SUBJECT: The authors measured infiltration rates in two mobile homes and attempted to relate infiltration to wind speed and indoor-outdoor temperature difference.

METHODOLOGY: A mobile home with caulking used as a sealant at all joints was alternatively tested with and without skirting. The second home tested was assembled with continuous sheathing board and was provided with skirting. It did not, however, have caulking. Carbon monoxide was used as the tracer gas in a common infiltration rate measurement procedure.

RESULTS: During the summer, the mobile home with caulking had an infiltration rate range of 0.096 air changes per hour (ACPH) to 1.030 ACPH. The second home had a range of 0.061 to 0.549 ACPH under similar conditions, thus demonstrating the benefits of continuous sheathing. The infiltration rates showed a dependence on wind velocity squared and a linear dependence on temperature. Seperate relations for each home fit the data very well.

As yet unpublished data for wintertime conditions are briefly referenced. For design conditions of 3°F external temperature and a wind speed of 15 mph, the home with caulking had an infiltration rate of 1.53 ACPH. The other home had a rate of 0.83 ACPH.

COMMENTS: The expressions presented to relate infiltration rate to other parameters are unique to the homes tested. The ranges of rates measured are not untypical of residential construction, but are higher than might be expected for these factory-produced mobile homes.

AUTHOR: Grimsrud, D.T.; M.H. Sherman; R.C. Diamond; P.E. Cordon; A.H. Rosenfield

TITLE: Infiltration -- Pressurization Correlations: Detailed Measurements on a California House

SOURCE: ASHRAE Transactions,85, 1979

SUMMARY: Infiltration studies were carried out in a typical tract home in the San Francisco area. Due to the mild climate, houses in this region were said to be loosely constructed and to show large air leakage rates.

Infiltration rates varied from approximately 0.33 to 1.25 air changes per hour over a range of weather conditions when measured by a tracer gas technique using nitrous oxide. In addition to weather data taken on site, pressure sensors mounted on the exterior walls were critical in establishing a pressure model for infiltration and showed a significant fluctuating component. Measured inside-outside pressure differences were less than a tenth of those expected based upon wind measurements made on site. Measurements also showed significant duct leakage and air flow between the attic, living space and crawl space.

COMMENTS: There are two significant findings in this work vis-a-vis the objectives of the current investigation. One is that homes in mild climates are likely to be more loosely constructed than those in more severe climates. The other is that the pressure differences measured for this well-shielded home were very low compared to those estimated by the measurement of wind velocities above the roof of the house.

AUTHOR: Grimsrud, D.T.; M.H. Sherman; R.C. Diamond; R.C. Sonderegger

TITLE: Air Leakage, Surface Pressures and Infiltration Rates in Houses

SOURCE: Lawrence Berkeley Laboratory, Univ. of Cal. Berkeley, Report No. LBL-8828, March 1979

SUMMARY: A model is discussed that uses air leakage data obtained under fan pressurization and the natural pressure differences between indoors and outdoors to predict the natural air infiltration rate of a house. Testing of the model on six homes shows fairly good agreement between infiltration rates measured using a tracer gas and those calculated from the model. Three of the 6 homes were in California and had measured rates between 0.15 and 1.36 air changes per hour (ACPH) over a wide range of environmental conditions. The individual ranges were 0.15 to 0.61, 0.50 t0 0.69, and 0.64 to 1.36 ACPH. Three modern, tightly built homes in the mid-west had rates of 0.08 to 0.13, 0.10 to 0.12, and 0.31 to 0.42 ACPH.

COMMENTS: The authors note the fact that the model does not account for pressure differences caused by indoor-outdoor temperature differences. Of interest is their observation that the low infiltration rates in two of the new, energy-efficient homes could lead to indoor air quality problems.

AUTHOR: Grot, R.A.; R.E. Clark

TITLE: Air Leakage Characteristics and Weatherization Techniques for Low-Income Housing

SOURCE: Paper presented at DOE/ASHRAE Conference on Thermal Performance of Exterior Envelopes of Buildings, Orlando, Florida, December 1979

SUBJECT: This rather unique study provides and analyzes air infiltration data on 266 dwellings occupied by low-income housholds in 14 cities in all major climatic zones of the U.S. Estimates are presented of the reduction in induced air exchange rates achievable by applying building weatherization techniques.

METHODOLOGY: Natural and induced air infiltration rates were measured respectively with a tracer-gas decay technique and a fan depressurization test.

RESULTS: Of a total of 1048 readings obtained using the tracer gas technique, it was found that ~19% were rates less than 0.5 air changes per hour (ACPH), 40% were moderate rates between 0.5 and 1.0 ACPH, 20% were high rates between 1.0 and 1.5 ACPH, and 20% were very high rates of greater than 2.0 ACPH. The geometric mean for all rates was 0.86 ACPH while the arithmetic mean was 1.12 ACPH. Results were distributed approximately lognormally. Preliminary results showed that conventional building weatherization options can reduce induced air change rates from 5 to 96%. It was further determined that there is no clear relationship between natural infiltration and induced air exchange rates.

COMMENTS: Most of the measurements of natural air infiltration were carried out in January to June 1979, averaging about four times for each dwelling. One problem with the data is that there was no attempt to consider the effects of wind velocity, indoor-outdoor temperature differences, or other factors that influence infiltration. It is inherently assumed that the large sample size negates differences due to these effects.

AUTHOR: Handley, T.H.; C.J. Barton

TITLE: Home Ventilation Rates: A Literature Survey

SOURCE: Oak Ridge National Laboratory Report No. ORNL-TM-4318, Environmental Sciences Division, September 1973

SUBJECT: A survey was made of published ventilation and infiltration rates in residences to identify a range to be utilized in calculations of doses resulting from home exposure to airborne radionuclides present in natural gas.

METHODOLOGY: The authors collected and reviewed a selection of the major papers dealing with infiltration rates in residences, spoke with a few experts in the field, and developed their conclusions.

RESULTS: The authors conclude that the average annual ventilation rate of most occupied houses falls in the range of 0.5 to 1.5 air changes per hour. The upper limit is raised to 2.0 air changes per hour when apartments in modern high-rise buildings are considered and if all ventilation air is from outside the building.

COMMENTS: The authors have made a fair assessment of the current situation in regards to occupied houses and average annual rates. They fail to consider, however, that actual rates may be much lower than 0.5 per hour at times, and that such time periods may extend for days or months.

AUTHOR: Harris-Bass, J.; B. Kavarana; P. Lawrence

TITLE: Adventitious Ventilation of Houses

SOURCE: Build. Serv. Eng., 42, 106-111, 1974

SUBJECT: Research undertaken by the British Gas Corporation on air infiltration into homes is described. The objective was to determine the practical extent to which homeowners could reduce infiltration rates by the application of draft-reducing techniques.

METHODOLOGY: A series of test house studies were conducted to quantify the relative reduction in the total area of openings and cracks by the application of typical methods of draft-proofing, such as weather-stripping of doors and double-glazing of windows. Opening areas were determined by direct measurement and by use of a "pressure/extract" technique using an exhaust fan and pressure drop sensing devices. Helium tracer gas and a whirling arm Katharometer were used to measure infiltration rates in various homes (results not given). Some preliminary work was done in wind tunnel and analytical modelling.

RESULTS: The test house results indicated that a 50% reduction in opening areas can be achieved by the fitting of foam-backed carpet over suspended floors. Reductions of up to 80% in individual components such as doors and windows were observed after careful installation of foam-backed weather-stripping. The authors concluded that although infiltration rates could be reduced 60-70% overall through these techniques, the open area available would still be very significant.

COMMENTS: The paper gives very little in the way of hard data that might be useful to the current investigation. The only significant result is the finding that infiltrations rates in English homes can be reduced 60-70% by homeowners with little effort.

AUTHOR: Heldenbrand, J.L., ed.

TITLE: Design and Evaluation Criteria for Engery Conservation in New Buildings

SOURCE: National Bureau of Standards, Report No. NBSIR 74-452 Revised February 1976

SUBJECT: This document presents a set of design and evaluation criteria for energy conservation in most types of new buildings. The National Conference of States on Building Codes and Standards (NCSBCS) requested that the National Bureau of Standards (NBS) develop the document with the intent that it could serve as the basis for a national standard developed through the voluntary consensus process. The resulting criteria focus on building subelements and service system arrangements.

METHODOLOGY: The criteria were developed by a task group comprised of representatives from the NBS Center for Building Technology, the American Consulting Engineers Council (ACEC), the American Institute of Architects (AIA), the NCSBCS, and the American Society of Heating, Refrigerating, and Air Conditioning Engineers (ASHRAE). It is largely based on existing standards and recommendations with the input of engineering judgement and advice from task group members and officials of various industry associations.

RESULTS: The criteria include the specification that "the natural (not mechanically forced) leakage of air between indoors and outdoors shall not exceed 0.7 air changes per hour for one - and - two family dwellings and 0.5 air change per hour for all other buildings and mobile homes." The limitations are "based on what is attainable in construction practice including allowance for exhaust fan openings fitted with self-closing devices when the fan is not in use." Compliance with the requirement is to be demonstrated by calculations from certified data furnished by manufacturers or suppliers of building materials and subelements supplemented by calculations using the crack method given in the ASHRAE Handbook of Fundamentals at the appropriate prevailing design wind conditions for the area of application. Windows, storm windows, doors, and exterior walls are all to be constructed in accordance with specified national and industry standards for air leakage. Caulking, sealants, or gasketing meeting listed requirements are to be used at all joints and penetrations through which air may enter.

COMMENTS: It is notable that the maximum infiltration rate limits proposed are based on what is attainable in construction practice. Possible impacts on indoor air quality were not recognized.

AUTHOR: Hollowell, C.D.; J.V. Berk; Chin-I Lin; I. Turiel

TITLE: Indoor Air Quality in Energy Efficient Buildings

SOURCE: Lawrence Berkeley Laboratory, Univ. of Ca./Berkeley Report No. LBL-8892, March 1979

METHODOLOGY: A mobile laboratory designed specifically for studies of indoor air quality and energy utilization in buildings was used to characterize pollutant concentrations at five sites, three of which were specially designed homes with average infiltration rates in the range of 0.2 to 0.3 air changes per hour. Tracer gas techniques were used to measure infiltration rates under a variety of environmental conditions.

RESULTS: Preliminary results indicated that the indoor levels of several pollutants exceed levels found outdoors in occupied homes. Nitrogen dioxide levels, although higher, were below air quality standards in a home using gas for cooking. The most troublesome pollutant monitored appeared to be formaldehyde/aldehyde concentrations. These often exceeded U.S. and European Standards for indoor air in residential buildings. As expected, the levels of certain contaminants for which primary sources were outdoors were lower indoors due to the shielding effect of low ventilation rates.

COMMENTS: The authors' approach to investigating the potential indoor air quality problem due to reduced infiltration rates was quite good. They simultaneously measured indoor and outdoor pollutant levels in occupied homes with known infiltration rates for a 8 to 9-day sampling period, thus allowing the indoor/outdoor relationship to be well-defined.

AUTHOR: Hollowell, C.D.; J.V. Berk; G.W. Traynor

TITLE: Impact of Reduced Infiltration and Ventilation on Indoor Air Quality

SOURCE: ASHRAE Journal, 49-53, July 1979

SUMMARY: The authors discuss potential health problems resulting from increases in indoor contaminant levels due to decreases in infiltration and ventilation rates. Special attention is given to nitrogen dioxide and carbon monoxide emissions from gas stoves, formaldehyde from building materials, and radon from building materials, tap water, and soil. Of particular interest are experimental results giving the concentrations of carbon monoxide and nitrogen dioxide in the air of a room containing a gas stove when a variety of ventilation rates are applied and the stove is operated for 1 hour.

COMMENTS: This paper clearly demonstrates the potential adverse impact of reduced infiltration rates on indoor air quality. It should be recognized, however, that the experimental conditions (i.e. room volume and duration of stove use) may not be representative of actual conditions in the residential environment.

AUTHOR: Houghten, F.C.; C.C. Schrader

TITLE: Air Leakage Through the Openings in Buildings

SOURCE: ASHRAE Transactions, 30, 105-120, 1924

SUMMARY: This report deals with a method employed to investigate air leakage through double hung windows in a brick wall plastered on the inside with cement plaster. Results are given for leakage through the window without weatherstripping, with two types of weatherstripping around the frame, and through the brick wall itself. A variety of other factors such as quality of workmanship, locking of windows, and painting of walls are also considered.

COMMENTS: The results show that the amount of air leakage through the test assembly is very sensitive to all the factors considered, with a very important single factor in the absolute sense being locking of the windows. Of interest is that weatherization options have considerably greater impact at high wind speeds than low wind speeds.

AUTHOR: Howland, A.H.; D.E. Kunber; R.F. Littlejohn

TITLE: Measurements of Air Movements in a House Using a Radioactive Tracer Gas

SOURCE: J. Inst. Heat. Vent. Eng., 28, 57-71, 1960

SUBJECT: Experiments are described in which radioactive Krypton gas was used to measure air movements and air change rates in a typical, detached suburban house in England.

METHODOLOGY: The tracer gas noted above was used in conjunction with Geiger-Muller tubes and a system of thermocouples to monitor air movements and air change rates. Variables included the type of heating system used (open fires, hot water radiators), and the opening and closing of various flues, doors, and windows.

RESULTS: The results demonstrate the effect of various heating and ventilation practices on the air flow patterns and movements that take place in a house.

COMMENTS: The problems addressed by this paper are mostly pertinent to types of construction that are uncommon if not non-existent in the United States. There is some value, however in the way the paper highlights the subtle interactions that may take place between various forces and how they can affect heating and ventilation system efficiency.

AUTHOR: Hunt, C.M.; D.M. Burch

TITLE: Air Infiltration Measurements in a Four-Bedroom Townhouse Using Sulfur Hexafluoride as a Tracer Gas

SOURCE: ASHRAE Transactions, 69, 186-200, 1963

SUBJECT: A factory-produced four-bedroom, two-story townhouse was assembled on its foundation in a high-bay environmental chamber to investigate the variation of infiltration rate with inside-outside temperature differences when wind velocity is negligible. Also considered was the effect of sealing doors and ducts.

METHODOLOGY: Sulfur hexafluoride was introduced into the circulating fan of the home's forced-air system and distributed throughout the house. Air samples were taken using three different sampling methods for comparison purposes. Samples were analyzed with a small gas chromatograph equipped with an aluminum oxide column and a pulsed mode electron capture detector. In separate measurements, helium and sulfur hexafluoride were used simultaneously as tracers to compare results.

RESULTS: The three sampling methods for sulfur hexafluoride included manual collection with a handpump and ballon going from room to room in a timed sequence; collection through a sampling network consisting of 16 polyethylene tubes; and collection from the return air at the entrance to the main ventilating fan in the central air system. Although there was greater scatter of some individual points, the three methods generally gave results within 0.06 air changes per hour over a 50 deg F range of inside-outside temperature difference. No difference was seen in results when the furnace fan was operated intermittently (8 minute intervals) as opposed to being operated continuously. Overall, the infiltration rate varied from about 0.2 ACPH at a temperature difference of 9.6 deg F to 0.6 ACPH at a difference of 52.3 deg F.

Sealing of the ducts to the kitchen, bathroom and clothes dryer fans resulted in a decrease in infiltration rate that was small compared to normal statistical variations in data. No further decrease was observed when doors were also sealed. However, when a 150 cm^2 make-up air opening in the floor of the furnace compartment was also sealed, the rate dropped from about 0.58 ACPH to 0.37 ACPH, thus indicating that door cracks and duct openings play a small role under conditions of low wind velocity.

Comparison of results using helium and sulfur hexafluoride as tracer gases led to the authors' conclusion that molecular diffusion plays no more than a secondary role in determining air infiltration rates.

Analysis of the effects of imperfect mixing of the tracer gas indicated that large errors would be accompanied by noticeable departure of tracer dilution rates from the first order decay law. Alternatively, small errors could be masked by normal variations in concentrations. Biases of up to 5 percent of reported values were noted as possible due to deparature from Beer's law during analyzation of air samples. Another potential error source was noted as involving drift in instrumental response with time.

COMMENTS: Differences in results when helium was used as the tracer were not adequately explained, since the helium results averaged about 14 percent less than those obtained using sulfur hexafluoride.

AUTHOR: Hunt, C.M.; S.J. Treado; B.A. Peavy

TITLE: Air Leakage Measurements in a Mobile Home

SOURCE: National Bureau of Standards Report No. NBSIR 76-1063, NTIS No. PB257102, July 1976

METHODOLOGY: Air leakage measurements were made in a mobile home using a tracer gas technique and a fan pressurization-depressurization method. The home was located in an environmental chamber so that it would be possible to measure and control temperatures. External fans were used to simulate wind forces acting on the structure. The mobile home was built in accordance with ANSI Mobile Home Standard A119.1 (1974).

RESULTS: Measured infiltration rates under no wind conditions were mostly between 0.4 and 0.6 air changes per hour (ACPH). When fans were used to simulate an 8 mph wind and indoor-outdoor temperature differences were varied, the range became 0.55 to 0.7 ACPH, or about 0.1 to 0.3 ACPH higher than the average values with no fans operating. A variety of experiments with and without storm windows installed showed that their effect was quite small. Furnace fan operation was seen to contribute 0.2 ACPH to results. When the front door to the home was opened, measured rates were on the order of 2 to 4 ACPH.

COMMENTS: This report is valuable in demonstrating the effects of wind, indoor-outdoor temperature differences, furnace fan operation, the use of storm windows, and the effect of an open door on the infiltration rate.

AUTHOR: Hunt, C.M.; S.J. Treado

TITLE: A Prototype Semi-Automated System for Measuring Air Infiltration in Buildings Using Sulfur Hexafluoride as a Tracer

SOURCE: National Bureau of Standards (NBS), Technical Note 898, March 1976

SUMMARY: A system is described which automatically operates a small gas chromatograph and measures parts per billion concentrations of sulfur hexafluoride (SF_6) in air. It samples air on a 10 minute cycle and records the response on a strip chart recorder.

COMMENTS: This brief report provides a comprehensive description of how SF_6 can be used to measure infiltration rates. It fully discusses the capabilities and limitations of the technique.

AUTHOR: Hunt, C.M.; J. Porterfield; P. Ondris

TITLE: Air Leakage Measurements in Three Apartment Houses in the Chicago Area

SOURCE: National Bureau of Standards, Report No. NBSIR 78-1475, NTIS Report No. PB283722, June 1978

SUBJECT: The authors present the results of air infiltration measurements in three apartment houses.

METHODOLOGY: Air infiltration rates were measured with a sulfur hexafluoride tracer gas technique and with a fan pressurization-depressurization method involving placement of a fan in a doorway of each apartment tested. The effect of sealing windows, doors, and fireplaces was investigated. The infiltration rate measured in one building was compared to the rate predicted by the ASHRAE crack method.

RESULTS: Two of the buildings, identified as Windsor and Kenmore, were older structures in tenement areas of the city. The third building, called Custer, was a newer building in a more suburban area. Under the varying conditions of the tests, Windsor had an average overall infiltration rate of 0.94 air changes per hour (ACPH), Kenmore had a rate of 1.2 ACPH, and Custer experienced 0.82 ACPH. At Windsor and Kenmore, the indoor-outdoor temperature difference was about 10°F. At Custer, it started at 4°F and increased to about 30°F during tests. Wind velocities in the immediate vicinity of the buildings were not recorded, although data from nearby airports were obtained and given for descriptive purposes.

Among the conclusions or observations that can be drawn from the data or its analysis are the findings that:

- Upper floors have somewhat greater infiltration rates on the average than lower floors;
- Kenmore had a higher air exchange rate than Windsor even though it had received caulking and weatherstripping treatment and had doorways to hallways that fit better. This finding and other data suggested that windows and doors only provide a small fraction of the overall leakage.

- Depressurization measurements at Custer showed that a slightly opened window can lead to a doubling of the air change rate in an apartment.

- Infiltration rates measured were considerably lower than those calculated from simple impact wind pressures using the ASHRAE crack method.

- Fan pressurization tests indicated that the exposed cracks around windows and doors which would be included in a crack length survey do not account for all the leakage paths in an apartment.

- Results indicated that there is no simple extrapolation that will permit prediction of natural infiltration rates from fan pressurization measurements.

COMMENTS: Significant findings of the study were that the ASHRAE crack method of infiltration rate estimation has severe limitations and that windows and doors comprise a relatively small fraction of leakage paths.

AUTHOR: Janssen, J.E.; J.J. Glatzel; R.H. Torborg; U. Bonne

TITLE: Infiltration in Residential Structures

SOURCE: Proceedings of the ASME Symposium on "Heat Transfer in Energy Conservation", Atlanta, Georgia, 1977

SUMMARY: The authors describe the tracer-gas decay technique they used to measure the infiltration rates in 12 residences and discuss the results. They find that contemporary homes in the mid-west exhibit infiltration rates of 0.4 to 0.6 air changes per hour (ACPH) under normal conditions if equipped with double glass windows, that rates are around 0.75 ACPH when single glass windows are installed, and that poor fitting windows and doors give infiltration rates of around 1.0 ACPH. They also note that infiltration usually, but not always, increases somewhat when furnaces are operating, and that a strong, gusty wind and an open fireplace damper can double the infiltration rate.

COMMENTS: There are quite a few factors influencing infiltration rates that the authors did not address, and this raises some doubt as to the validity of their specific conclusions. Nevertheless, the paper provides useful data on the general range of infiltration rates to be expected in modern homes.

AUTHOR: Jennings, B.H.; J.A. Armstrong

TITLE: Ventilation Theory and Practice

SOURCE: ASHRAE Transactions, 77, 50-60, 1971

SUBJECT: This paper discusses building ventilation requirements in terms of the air volumes needed to dilute body odors and cigarrette smoke to acceptable levels.

METHODOLOGY: The authors review the experimental work of various researchers concerned with odor dilution, discuss fresh air requirements for oxygen replenishment purposes, and derive an analytical model that represents the interaction between ventilation rates, room volumes, and contaminant concentrations.

RESULTS: The data and analysis demonstrate that maintenance of an acceptable contaminant concentration level within an enclosed space is a function of the contaminant source strength, volume of the space, and rate of dilution ventilation. A particularly pertinent conclusion is that insufficient recognition has been given to the need for making more effective use of recirculated air in systems in which the air can be washed, deodorized or cleaned.

COMMENTS: The paper does not address the impact of infiltration or the need to ventilate to dilute concentrations of contaminants of immediate concern. Nevertheless, it provides an excellent introduction to the overall subject area of contaminant control and to the basic principles by which the impact of reduced infiltration rates can be assessed.

AUTHOR: Keast, D.N.

TITLE: Acoustic Location of Infiltration Openings in Buildings

SOURCE: Final Report to Brookhaven National Laboratory under Contract No. 427075-S, Report No. BNL-50952, October 1978

SUMMARY: This report describes low-cost, readily available equipment and procedures whereby the average building contractor or homeowner can use acoustic leak location methods to pinpoint many of the air infiltration openings in a building.

COMMENTS: An interesting comment in the report (pg 76) notes that the researchers were unable to interest members of the National Home Improvement Council (NHIC) in Houston and Los Angeles in a program to test the leak location method. A NHIC affiliate in Houston explained that there was at the time no significant commercial market for building-energy conservation products and services in those warmer cities. Heating requirements are small, and electric rates for air-conditioning are one-half to one-third of those in the northeastern part of the country. Indeed, contractors in the Houston area who invested in equipment to install insulation were finding the equipment "painfully idle."

AUTHOR: Kelhnofer, W.J.

TITLE: Air Infiltration in Buildings Due to Wind Pressures Including Some Neighboring Body Effects

SOURCE: Proceedings of the ASME Symposium on "Heat Transfer in Energy Conservation," Atlanta, Ga., 1977

SUMMARY: A procedure is developed for calculating air infiltration rates due to wind pressures on the exterior walls of buildings assuming no chimney and mechanical ventilation effects and minimal internal resistance to air flow. Using the results of wind tunnel tests, calculations are presented showing the effects a single neighboring building can have on the infiltration rates. Relative building heights, distance between buildings, and wind direction are varied, and both uniform and shear flows are considered. The results show that depending on the particular two-body configuration, a neighboring body can cause either a decrease or increase in infiltration rates.

COMMENTS: This paper helps to confirm the contention that the microclimate in the vicinity of a particular building cannot be accurately characterized in terms of wind velocities measured over roofs or at relatively distant locations.

AUTHOR: Lagus, P.L.

TITLE: Characterization of Building Infiltration by the Tracer Dilution Method

SOURCE: Technical Bulletin 77-1; Systems, Science, and Software La Jolla, California 92038

SUMMARY: The author briefly reviews the procedure for using sulfur hexafluoride as a tracer gas in determining the infiltration rate of a structure. Attention is given to residential buildings as well as large multi-story structures.

COMMENTS: The paper provides a basic introduction to the overall subject area of using tracer gases to measure ventilation rates.

AUTHOR: Laschober, R.R.; J.H. Healy

TITLE: Statistical Analyses of Air Leakage in Split-Level Residences

SOURCE: ASHRAE Transactions, 70, 364-374, 1964

SUBJECT: Infiltration rates were measured in two research houses of split-level design. Collected data were statistically analyzed to determine whether infiltration could be successfully related to outdoor temperature and wind conditions.

METHODOLOGY: Infiltration rates were measured using helium as a tracer gas and a katharometer furnished by the National Bureau of Standards. Also monitored were wind speeds, wind directions, and indoor-outdoor temperature differences. The resulting data were analyzed to identify relationships with statistical significance.

RESULTS: The first house studied had an unusually designed second level roof that may have influenced the magnitude of infiltration rates. In addition, it had an uncommon "valence" type heating system and other experimental features. When high wind conditions (14.2-14.6 mph) and large indoor-outdoor temperature differences (57.3°-74.7°F) prevailed simultaneously during some tests, infiltration rates in the range of 2.3-2.67 air changes per hour (ACPH) were measured for the entire house. At the other extreme, when the wind speed was 2.5 mph and the temperature difference was only 1.0°F, the infiltration rate was as low as 0.32 ACPH.

The second house was built to specifications provided by a building contractor and was similar in most respects to typical houses of this type. The heating system consisted of a full perimeter air distribution system used in conjunction with either a gas-fired or electric furnace. With the electric furnace in operation, the infiltration rate for the whole house ranged from 0.23 to 1.6 ACPH. With the gas-furnace, the range was 0.30 to 1.79 ACPH. Analysis of the data indicated that gas-furnace operation increased the infiltration rate by 0.14 to 0.16 ACPH, primarily in the lower level where the furnace was located.

While discussing the validity of ASHRAE methods for estimating infiltration rates, namely the crack and air change methods, the authors note that these methods do not easily allow the user to consider the effect of temperature differences on the infiltration rate, and that these effects are seldom considered. With reference to the infiltration rates measured in their study, they conclude that methods currently accepted for estimating residential infiltration rates provide values considerably less than those indicated by tests.

COMMENTS: The data are useful for demonstrating the variation in infiltration rates with wind speeds, wind directions, and indoor-outdoor temperature differences. The supported finding that current infiltration estimation methods underestimate rates is significant.

AUTHOR: Lee, B.E.; M. Hussain; B. Soliman

TITLE: Predicting Natural Ventilation Forces Upon Low-Rise Buildings

SOURCE: ASHRAE Journal, 35-39, February 1980

SUMMARY: The authors note that the ASHRAE method for estimating the pressure difference across a building due to wind forces may result in considerable error when the result is subsequently used to estimate infiltration rates. They then describe a wind tunnel investigation conducted to determine the wind pressure forces that act on a low-rise building that is part of a large group of similar buildings, and finish with the presentation of a new prediction method for estimating the pressure difference across a building.

COMMENTS: One of the problems with some prior studies attempting to relate wind speeds to observed infiltration rates in buildings stems from the use of wind velocity data from weather stations at distant locations. These weather stations typically measure velocities at a height of 10 meters, well above the roof height of most residences. In addition, they are usually sited in open areas such as airports. The procedure presented by these authors should help in better defining the microclimate in locations that are somewhat shielded from the full force of the wind.

AUTHOR: Luck, J.R.; L.W. Nelson

TITLE: The Variation of Infiltration Rate with Relative Humidity in a Frame Building

SOURCE: ASHRAE Transactions, 83, 718-729, 1977

SUMMARY: While making infiltration rate measurements in a one-story frame house, the authors discovered a possible relationship between relative humidity and infiltration rate. They hypothesize that swelling or shrinking of the wood with changes in humidity can affect crack dimensions. A calculation presented demonstrates that crack dimensions around a normal double-hung window may be reduced by about 50% when the relative humidity increases from 20 to 40%.

COMMENTS: The authors findings make sense and could partially explain why others have obtained erratic results when trying to relate infiltration rate to environmental factors without considering humidity.

AUTHOR: Malik, N.

TITLE: Field Studies of Dependence of Air Infiltration on Outside Temperature and Wind

SOURCE: Energy and Buildings, 1 (3), 281-292, April, 1978

SUBJECT: The air infiltration rate measured in two similar townhouses is parametrized in terms of wind speed, wind direction, indoor-outdoor temperature difference, average rate of furnace firing, and fraction of time that doors are open.

METHODOLOGY: Air infiltration rates in two identical townhouses were measured over several winter months using a sulfur hexafluoride tracer gas method. Weather variables were monitored at a nearby weather station. The data obtained were statistically analyzed to determine and test the significance of relationships.

RESULTS: Simultaneous measurements of air infiltration and rate of energy consumption (with gas heat) proved that gas consumption is greater, for the same indoor-outdoor temperature difference, when the infiltration rate is higher. For one particular townhouse, air infiltration contributed 24, 38, and 48% of the heat loss when the air infiltration rate was respectively 0.5, 1.0, and 1.5 air changes per hour (ACPH). These results were in general agreement with the rule of thumb that air infiltration typically accounts for one third of all heat losses in conventional residential housing when the infiltration rate averages about 0.75 ACPH.

The data indicate that opening the front door of a house increases the infiltration rate and that the effect is enhanced if the basement door is also opened. Furnace operation was found to increase the rate by 0.24 ACPH on the average, and wind velocity and indoor-outdoor temperature differences influenced the rates as would be expected. At low wind speeds (less than 6 mph) the infiltration rates in the two houses increased about linearly from about 0.15 to 0.7 ACPH as the temperature difference varied from about 0 to 56°F. At negligible wind speed and temperature difference, the rate was 0.193 ACPH in one house. When wind speeds were between 10 and 20 mph, the infiltration rates varied from about 0.3 to 1.6 ACPH as the temperature difference ranged from about 20 to 50°F. Wind direction had a demonstrable effect on results.

COMMENTS: The paper presents numerous empirical equations derived from the data that are unique to the houses studied. More might have been done to define the impact of various obstructions to wind flow on the microclimate in the vicinity of each home.

AUTHOR: Moschandreas, D.J.; J.W.C. Stark

TITLE: The GEOMET Indoor-Outdoor Air Pollution Model

SOURCE: EPA Report No. EPA-600/7-78-106, NTIS Report No. PB285706, February, 1978

SUBJECT: A model is presented for estimating indoor air pollutant concentrations in residences as a function of outdoor pollutant levels, indoor pollutant generation source rates, pollutant chemical decay rates, and air exchange rates. Topics discussed include basic principles, model formulation, parameter estimating, model statistical validation, and model sensitivity to perturbations of the input parameters.

METHODOLOGY: The numerical simulation model presented follows the general principles of a mass balance equation. In contrast to most prior models, the model can represent transient behavior. As a result, it is possible to model both short- and long-term intervals. Since it is usually difficult to measure the infiltration rate and indoor contaminant generation source rate, the authors developed a method to back-calculate values for these parameters from measured indoor and outdoor pollutant concentrations.

RESULTS: Model estimated indoor pollutant levels were within 25% of the observed indoor values for CO, NO, non-methane hydrocarbons, CH_4, CO_2, and NO_2. Ozone predictions were somewhat less accurate but still adequate. Predictions for SO_2 were not validated.

COMMENTS: Given accurate input data, this model appears to have the potential to adequately represent the interactions between parameters of concern. One is forced to use the word "potential", because agreement between model predictions and observed values was somewhat due to the fact that infiltration rates and pollutant generation rates were specially selected to minimize errors. Although there was some attempt to validate the estimated infiltration rates, there was no effort to do the same with contaminant generation rates.

AUTHOR: Moschandreas, D.J.; J.W.C. Stark; J.E. McFadden; S.S. Morse

TITLE: Indoor Air Pollution in the Residential Environment. Volume I: Data Collection, Analysis and Interpretation; Volume II: Field Monitoring Protocol, Indoor Episodic Pollutant Release Experiments and Numerical Analyses.

SOURCE: EPA Report No.'s EPA-600/7-78-229a and -229b, December 1978

SUMMARY: This 2-volume set of final reports describes the findings of a major study sponsored by the EPA and HUD to investigate air quality in the indoor residential environment and the factors that influence air quality. The study clarified several aspects of the overall problem area and demonstrated that indoor air quality may present quite different exposure conditions than the surrounding ambient air quality. Additionally, it determined (somewhat vaguely) that the retrofitting of existing residences down to an air exchange rate between 0.4 and 0.6 air changes per hour conserves energy without inducing drastic deterioration of the indoor air quality.

COMMENTS: These reports contain a considerable amount of pertinent and important data on the overall subject area, particularly in regards to the influence of important factors on indoor air quality.

AUTHOR: Peterson, J.E.

TITLE: Estimating Air Infiltration Into Houses: An Analytical Approach

SOURCE: ASHRAE Journal, 60-62, January 1979

SUMMARY: Based on the results of nine previous experimental studies of air infiltration in houses, the author discusses and presents two very general and simple approaches to estimating the infiltration rate of a house. Both require educated guessing as to whether the house is tightly constructed, loosely constructed, or somewhere in between.

COMMENTS: The author's approach is attractive because of its simplicity and its qualitative and quantitative consideration of a number of important factors. It has some uses where one wishes to define typical infiltration rates for broad categories of housing. By no means, however, can it be considered accurate for predicting the infiltration rate of a specific home under a given set of environmental conditions.

AUTHOR: Reeves, G.; M.F. McBride; C.F. Sepsy

TITLE: Air Infiltration Model for Residences

SOURCE: ASHRAE Transactions, 85, 667-677, 1979

SUBJECT: The authors obtained and utilized over seven thousand observations of tracer gas concentrations, and observations of associated temperature differences, wind directions, and wind speeds, in an attempt to develop a generalized model of air infiltration for residences. The data were collected from nine research residences including 3 townhouse apartments and 6 one-and two-story residences. Also reported upon are the results of a review of 16 previous studies that attempted to relate infiltration rates to wind speeds and temperature differences with a linear model.

METHODOLOGY: Infiltration rates were measured using a sulfur hexafluoride tracer gas technique. The resulting data were utilized to test 8 models and to select the most successful one.

RESULTS: The review of previous studies indicated that there was no substantial consistency among the various results except for the fact that they generally suggested an air change rate on the order of 0.1 per hour under negligible wind conditions and indoor-outdoor temperature differences. A particular problem was that the statistical regression coefficients required for the linear model were essentially unique for each individual house.

A model formed from the physical variables and theory associated with air infiltration was the simplest and most successful of seven such models developed. Variables included the total equivalent crack length, the theoretical pressure difference across the enclosure due to indoor-outdoor temperature differences, and the pressure difference due to the wind. Fossil fuel heating systems with their attendant chimneys were found to cause an average increase of 12.5% in infiltration rates.

COMMENTS: It is not very clear how well the model functions when utilized with a mean value for the regression coefficient in the final model. Comparisons of measured values to predicted values in the paper appear to have been based on coefficients individually and specifically determined for the homes addressed. Thus, it is possible that this model has some of the same short comings as the linear models reviewed. A further potential problem with the model is that it does not address leakage sources other than those covered by the crack method of infiltration rate estimation presented by ASHRAE. Caffey (1979) suggests that the major source in a home is the bottom plate or base board area of the exterior wall.

AUTHOR: Ross, H.D.; D.T. Grimsrud

TITLE: Air Infiltration in Buildings: Literature Survey and Proposed Research Agenda

SOURCE: Lawrence Berkeley Laboratory, Univ. of Ca./Berkeley, Report No. LBL-7822, March 1979

SUBJECT: This work provides a briefly annotated bibliography of much of the published work in air infiltration up to and partially including 1977. In addition, the authors review the state-of-the-art in this subject area and propose further research to resolve limitations and shortcomings.

METHODOLOGY: The authors review the findings of the major studies of air infiltration and utilize the results to identify areas requiring further study. There is special emphasis on the development of models for air infiltration into residences and commercial buildings.

RESULTS: The authors found that several areas necessary for understanding the best means of simulating infiltration of any particular building type remain controversial or unaddressed. They propose further work in the modeling of air infiltration in commercial buildings and residential structures, in determining infiltration through open windows, in improving measurement techniques, and in the formation of a centralized data management center.

COMMENTS: This is a rather unique and comprehensive review of the state-of-the-art that does much to identify and discuss problem areas.

AUTHOR: Shepherd, P.B.; J.E. Gerharter

TITLE: Techniques for Control of Air Infiltration in Buildings

SOURCE: Final Report to U.S. Army Facilities Engineering Support Agency under Contract No. DAAK 70-78-D-0002, Report No. FESA-TS-2070, August 1979

SUMMARY: This report provides detailed methods for safe retrofitting of residential buildings to reduce air infiltration. A procedure for estimating the payback period for investment in infiltration reduction is included together with test procedures for measuring air infiltration in residences. The report also includes an extensive bibliography with 233 citations.

COMMENTS: The report does a good job of identifying the potential leakage paths in a house, and in describing procedures for measuring and reducing infiltration rates. Of special interest is the clear warning that infiltration should not be reduced to a level where the personal health and safety of building occupants is endangered. Based solely on judgements expressed in literature and interviews, the authors go out on a limb and recommend that the minimum number of building air changes per hour should be 1.5 when a special fan assembly is used to create a 0.1-inch of water pressure drop across the building envelope.

AUTHOR: Sinden, F.W.

TITLE: A Two-Thirds Reduction in the Space Heat Requirement of a Twin Rivers Townhouse

SOURCE: Energy and Buildings, 1(3), 243-260, 1978

SUBJECT: A townhouse was retrofitted to reduce annual energy use for space heating.

METHODOLOGY: The retrofits included interior window insulators of various designs, basement and attic insulation, and systematic attention to routes of air infiltration. Energy savings were determined for each of the modifications.

RESULTS: The author notes that air infiltration accounted for more than 35% of the heating fuel consumed before the house was retrofitted. Leak sources included the joint between wood and masonry at the top of the foundation, the open shaft around the metal flue, a variable gap between the masonary party wall and the wooden structure of the townhouse (in the attic), small leaks from the interior of the house to the attic, and leaks around windows and doors and along a number of outside joints. Sealing of these leaks reduced the air infiltration rate to between 0.2 and 0.4 air changes per hour even in windy weather.

After discussing difficulties in the determination or estimation of air infiltration rates, the author discusses potential problems associated with indoor air pollution when infiltration rates are lowered too far. He notes that the range of rates achieved in the townhouse are about as low as one would care to live with without opening a window. It is further said that most houses would be noticebly stuffy at lower rates.

COMMENTS: Only a small part of this paper deals with air infiltration. Nevertheless, the author has comprehensively addressed the overall subject area of infiltration.

AUTHOR: Sinden, F.W.

TITLE: Wind, Temperature and Natural Ventilation - Theoretical Considerations

SOURCE: Energy and Buildings, 1(3), 275-280, April 1978

SUMMARY: The author provides a theoretical discussion of the complex interaction between the two major driving forces for air infiltration, i.e., wind and convection induced by a temperature difference between indoors and outdoors. He concludes that the interaction is "bad news" for computer modelers since it appears unlikely that there exists any simple general formula that universally represents natural ventilation in buildings.

COMMENTS: This paper does much to explain the erratic results of numerous studies attempting to develop a simple empirical model to predict infiltration rates as a function of wind speeds and indoor-outdoor temperature differences.

AUTHOR: Stricker, S.

TITLE: Measurement of Air-Tightness of Houses

SOURCE: ASHRAE Transactions, 81, 148-167, 1975

SUBJECT: A technique for measuring the actual leakage area of houses was developed and demonstrated.

METHODOLOGY: The method of measuring the air-tightness of a house involves operating a powerful exhaust fan temporarily installed through an open window and measuring the resulting pressure drop in the house. This measurement combined with the fan pressure-flow characteristics, can be used to obtain the area of an opening that permits a similar air flow at the same pressure difference as that measured. The area of this opening is defined as the equivalent leakage area of the house, or ELA. The technique was applied to 24 houses. Also measured over a period of a month or so were weather conditions, indoor humidity levels, energy consumption, indoor air particulate levels, and other parameters.

RESULTS: The authors note that the ELA in three houses previously tested was 2.5 to 3 times greater than the leakage calculated by the ASHRAE crackage method, indicating that other major leak sources existed. Possibilities identified were plumbing and wiring openings and leaky headers and plates over foundation walls.

The data obtained in this study indicated that seemingly obvious correlations arrived at by known principles may not always be true and that much more must be gathered from a survey of this type. More specifically, it was found that the relationship between the size of an ELA for a house and the observed internal humidity was weak. Although the general tendency was that houses with relatively high leakage areas required more heating energy, the correlation here was also somewhat weak.

Homes with smokers generally had higher internal particulate levels than those without smokers. No significant differences were found in air cleanliness when only the type of heating system used was considered.

COMMENTS: The paper does not provide data on natural infiltration rates for the test houses, or on contaminant concentrations for anything other than undefined particulate matter. Discussion subsequent to presentation of the paper indicates that the ELA measurement method may have serious limitations when only a single pressure difference is used. Indeed, it is demonstrated that the ELA may be a function of the pressure difference as well as other factors.

AUTHOR: Tamura, G.T.; A.G. Wilson

TITLE: Air Leakage and Pressure Measurements on Two Occupied Houses

SOURCE: ASHRAE Transactions, 70, 110-119, 1964

SUBJECT: Air leakage measurements were carried out on two occupied one-story houses located in Canada. An attempt was made to relate the measured air leakage to weather conditions and to furnace operation.

METHODOLOGY: A helium tracer gas was used in conjunction with a katharometer to measure air infiltration rates. Indoor and outdoor pressures were measured with diaphragm, strain-gauge-type, pressure transducers. In addition, wind velocities and indoor-outdoor temperature differences were recorded. Both test houses were of insulated wood-frame construction with full basements and had forced warm-air heating systems with high pressure gun-type oil burners.

RESULTS: Over two winters, the infiltration rates measured in one house ranged from 0.25 to 0.41 air changes per hour (ACPH). During the interim summer period, the rates varied from 0.07 to 0.16 ACPH.

During the first winter, the rates in the other house ranged from 0.37 to 0.63 ACPH. With the openable windows taped in the second winter, the range was 0.33 to 0.57 ACPH. The range during the summer for this house was 0.11 to 0.23 ACPH.

The increase in air change rate for each mph of wind was 0.017 and 0.020 ACPH for the two houses respectively. At zero wind speeds and small temperature differences, infiltration rates were respectively 0.04 and 0.06 ACPH. In the first house, it was additionally found that an inside to outside temperature difference of 38°F induces the same total rate as that due to wind at 8 mph.

During the summer, when the temperature difference was small, the increase of infiltration rate with wind velocity was essentially linear. During winters, rates were impacted additionally by both house stack action and furnace action. The air change rate under the combined influence of wind and temperature was less than the sum of rates due to wind and temperature acting independently. Furnace operation was seen to increase rates up to 50%. There is an interesting discussion of how the measured rates compare with the rates calculated using the ASHRAE crack method.

COMMENTS: This is an excellent paper with much useful information. Of particular interest is a comment made by one of its authors during a subsequent discussion period. He noted that "there is a problem of relating air leakage characteristics of components to overall building leakage under specified conditions. The present basis of calculating air leakage by the crack method is quite arbitrary, and it would appear that any close agreement between measured and calculated values is largely fortuitous."

AUTHOR: Tamura, G.T.

TITLE: Measurement of Air Leakage Characteristics of House Enclosures

SOURCE: ASHRAE Transactions, 81, 202-211, 1975

SUBJECT: This paper describes a series of tests conducted on six wood-frame houses to separately establish rates of overall air leakage and leakage through windows, doors, walls, and ceilings.

METHODOLOGY: An exhaust fan was connected at the opening of a basement window in each house by a metal duct and was adjusted to provide a constant indoor-outdoor pressure difference of 0.30 in. of water (equivalent to 25 mph wind velocity head). Various parts of the house exteriors were covered with plastic sheets and sealed with adhesive tape such that leakage rates through remaining leakage paths could be measured.

RESULTS: The leakage rates of prime windows were in reasonably good agreement with those given in the ASHRAE Handbook of Fundamentals. Storm units were found to reduce window leakage values by 26 to 71 percent. Windows and doors with storm units consistently contributed from 15 to 24 percent of overall leakage values. The relative contribution of ceilings and outside walls was less clear, although it was evident that the amount of leakage varied with the type of wall construction.

COMMENTS: The paper does not provide any original data on the natural infiltration rates for the test sample of houses but has value in demonstrating the relative importance of various leakage paths. Discussion subsequent to presentation of the paper, however, suggested that the relative contribution of various leakage paths might change if other indoor-outdoor pressure differences were applied.

AUTHOR: Tamura, G.T.

TITLE: The Calculation of House Infiltration Rates

SOURCE: ASHRAE Transactions, 85, 58-71, 1979

SUBJECT: The author utilizes infiltration rate data from two prior studies on two houses to demonstrate a proposed calculation procedure for estimating infiltration rates in homes.

METHODOLOGY: The author separately addresses infiltration rates caused by stack action and wind action and then provides an equation for determining the combined effect. The procedure utilizes a considerable amount of site-specific information.

RESULTS: The proposed procedure for calculating infiltration rate gave values that agreed reasonably well with measured values. The average difference between measured and predicted values was 0.04 air changes per hour (ACPH) for one house and 0.07 for the other.

COMMENTS: The proposed calculation procedure has considerable potential for general application, especially if various shortcomings are resolved through the collection of further data and further refinement of individual subelements of the procedure.

AUTHOR: Tipping, J.C.; J.N. Harris-Bass; D.J. Nevrala

TITLE: Ventilation: Design Considerations

SOURCE: Build. Serv. Eng., 42, 132-141, 1974

SUBJECT: This paper outlines the basic requirements for a fresh air supply to a building while considering health, comfort, and air for combustion purposes. The feasibility of achieving these requirements by natural and mechanical means is discussed.

METHODOLOGY: Referring to data obtained in the study by Harris-Bass et al. (1974) and to other sources, the authors discuss fresh air requirements for respiratory requirements, removal of contaminated air, heat balance, and combustion air. In addition, they discuss the effects of flued gas appliances on infiltration rates, and discuss various mechanical means for ensuring an adequate supply of fresh air.

RESULTS: It was concluded or stated that: 1) fresh air requirements for respiratory needs are only a small fraction of requirements for other purposes; 2) a considerable amount of ventilation is necessary to remove heat gains during warm weather when the indoor-outdoor temperature difference is small; 3) gas or oil fired appliances require moderate amounts of air for combustion purposes; 4) a large variation in infiltration rate can be expected with changing wind speed and degree of air "tightness" in a building; 5) open flued appliances promote increased infiltration by both the stack effect and the wind; and 6) the fresh air supply required in a dwelling can be more effectively controlled by mechanical ventilation than by natural means.

COMMENTS: Like many other papers of this time period, this one assumes that internally generated contaminants in buildings simply include body odors, tobacco smoke, and "cooking smells". Much else that is discussed is common knowledge or not very pertinent to the current investigation.

AUTHOR: Treado, S.J.; D.M. Burch; C.M. Hunt

TITLE: An Investigation of Air-Infiltration Characteristics and Mechanisms for a Townhouse

SOURCE: National Bureau of Standards, Technical Note 992, August 1979

SUBJECT: Air infiltration measurements were performed on a three bedroom townhouse with a gas-fired, forced air furnace system to quantify the amount of air infiltration due to various mechanisms. General guidelines are presented for reducing air infiltration in residences.

METHODOLOGY: Air infiltration rates were measured using a tracer-gas technique and a pressurization method. A thermographic survey was performed in conjunction with pressurization of the structure to identify specific leaks. An apparatus for measuring the air permeability of building materials was used on solid building elements.

RESULTS: Under wind speeds of 2.0-3.0 mph and indoor-outdoor temperature differences of 6.4 to 41.7°F, the infiltration rate varied from 0.09 to 0.62 air changes per hour (ACPH) when the burner was off. Approximately 0.11 ACPH or 20% of the rate was principally attributed to air leakage at the seams of supply ducts located in interior wall cavities when the furnace blower was operating. The combustion and draft-diverter air requirements were measured and were found to correspond to an induced infiltration rate of 0.31 ACPH. Under winter conditions, it was estimated that 47.8% of the infiltration rate was due to leakage through walls, the floor/wall interface, and ceilings; 29.6% was due to burner and furnace blower operation; 6.2% was due to cracks around windows, doors, and electrical outlets; and the rest to other sources.

COMMENTS: A surprising finding to the authors was that air leakage through cracks around windows, doors, and electrical outlets accounted for only 6% or so of the overall air-infiltration rate. This finding however, is in agreement with other studies that have shown that caulking and weatherstripping around windows and doors does not always produce significant reductions in the overall air-leakage rate.