INDOOR POLLUTANTS

COMMITTEE ON INDOOR POLLUTANTS

BOARD ON TOXICOLOGY AND ENVIRONMENTAL HEALTH HAZARDS

ASSEMBLY OF LIFE SCIENCES

NATIONAL RESEARCH COUNCIL

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COMMITTEE ON INDOOR POLLUTANTS

JOHN D. SPENGLER, Harvard School of Public Health, Boston, Massachusetts, Chairman

MICHAEL D. LEBOWITZ, University of Arizona Medical Center, Tucson, Arizona, Cochairman

RONALD W. HART, National Center for Toxicological Research, Jefferson, Arkansas

CRAIG D. HOLLOWELL, University of California, Berkeley, California

MORTON LIPPMANN, New York University Medical Center, New York, New York

DEMETRIOS J. MOSCHANDREAS, GEOMET Technologies, Inc., Gaithersburg, Maryland

JAN A. J. STOLWIJK, Yale University School of Medicine, New Haven, Connecticut

DAVID L. SWIFT, The Johns Hopkins University, Baltimore, Maryland

JAMES E. WOODS, JR., Iowa State University, Ames, Iowa

JAMES A. FRAZIER, National Research Council, Washington, D.C., Staff Officer

NORMAN GROSSBLATT, National Research Council, Washington, D.C., Editor

LESLYE B. GIESE, National Research Council, Washington, D.C., Research Assistant

JEAN E. PERRIN, National Research Council, Washington, D.C., Secretary

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[redacted]

CONTRIBUTORS TO THE REPORT ON INDOOR POLLUTANTS

JAMES BERK, University of California, Berkeley, California

WILLIAM F. BRANDOM, University of Denver, Denver, Colorado

DAVID M. BURNS, University Hospital, San Diego, California

BENJAMIN BURROWS, Arizona Health Sciences Center, Tucson, Arizona

WILLIAM CAIN, Yale University School of Medicine, New Haven, Connecticut

ROY R. CRAWFORD, Iowa State University, Ames, Iowa

CHARLES W. DENNIGER, Stanley Consultants, Inc., Muscatine, Iowa

DOUGLAS DOCKERY, Harvard School of Public Health, Boston, Massachusetts

NURTAN ESMEN, University of Pittsburgh, Pittsburgh, Pennsylvania

HUGH EVANS, New York University Medical Center, New York, New York

ARTHUR FRANK, Mount Sinai School of Medicine, New York, New York

RALPH F. GOLDMAN, Institute of Environmental Research, U.S. Army, Natick, Massachusetts

JACK D. HACKNEY, Rancho Los Amigos Hospital, Downey, California

CHARLES M. HUNT, National Bureau of Standards, Washington, D.C.

GEORGE JAKAB, The Johns Hopkins University, Baltimore, Maryland

JOHN E. JANSSEN, Honeywell, Inc., St. Paul, Minnesota

EDUARDO A. B. MALDONADO, Iowa State University, Ames, Iowa

BOARD ON TOXICOLOGY AND ENVIRONMENTAL HEALTH HAZARDS

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Drs. John D. Spengler and Michael D. Lebowitz, Chairman and Cochairman of the Committee, prepared Chapters I, II, and III, on the basis of material submitted by the other members. Drs. Craig D. Hollowell and Demetrios J. Moschandreas coordinated the preparation of Chapters IV, V, and VI. Chapter VII was written under the direction of Drs. Lebowitz, Morton Lippmann and David L. Swift. Drs. Lebowitz and James E. Woods, Jr., collaborated in the preparation of Chapter VIII, and Dr. Woods prepared Chapter IX and Appendix B. Appendix A was compiled by Dr. Hollowell.

The whole manuscript was organized, reviewed, and approved by the full Committee.

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*Deceased.

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EXECUTIVE SUMMARY

Many people spend large amounts of each day indoors--in many cases, 80-90%--in a house, an automobile, a waiting room, an office or other workplace, or a confined space accessible to the general public, such as a store or a restaurant. It has been shown that indoor exposure to environmental pollutants can be substantial. Although there is little epidemiologic evidence on the health effects of indoor pollutants, indoor concentrations of some pollutants that already have primary ambient-air quality standards exceed those standards. Indoor exposure has been largely overlooked in research on the health effects of environmental pollutants, but it can constitute an important fraction of the total exposure to many pollutants.

Indoor pollution in residences, public building, and offices is created for the most part by the occupants' activities and their use of appliances, power equipment, and chemicals, by wear and tear and outgassing of some structural or decorative materials, by thermal factors, and by the intrusion of outdoor pollutants.

In some cases, the outdoor pollutants that penetrate to the indoors may represent the most important pollutant stress on human health and welfare, and such effects have been addressed at length in reports of previous National Research Council committees. This report is focused primarily on the indoor air contaminants that are liberated indoors. When they attain high concentrations, they may cause nuisances, irritation of sensitive tissues, illness, and death from acute as well as chronic exposures. Some pollutant sources--such as cigarette-smoking--have been recognized for a long time, but their importance has only recently been evaluated. Others arise from new products or from old products in new uses, such as building materials, pesticides, and insulation. A number of sources are of concern only in the indoor environment, e.g., cooking, use of consumer products, space-heating devices, and floor and wall coverings. The expanded use of wood and coal for residential space-heating, of home hobby and craft products, and of products that liberate organic substances is a potential contributor to the contamination of indoor environments. Infectious microbes and allergenic agents can grow indoors or be transmitted into indoor environments.

Throughout this report, pollutants are mentioned without discussion of their health effects. This does not constitute an oversight on the part of the Committee, but rather reflects a decision that the discussion here be adequate to show that there are indoor pollutants that cause adverse health effects in humans. The reader's attention is directed to Chapter III, which offers some recommendations for further health research with respect to these pollutants, for further exposure studies, and for public education about effective ways of reducing exposure to many contaminants encountered indoors. The Committee on Indoor Pollutants and its contributors prepared concise reviews of such physical aspects as sources and concentrations and of such biologic aspects as the physiologic and toxicologic effects of a variety of contaminants encountered indoors. In addition, the effects of those contaminants that bear on human well-being in a more general way, such as soiling and corrosion, and the available means of controlling the presence of the contaminants are discussed in some detail. The report attempts to focus personal, corporate, and government attention on present and potential problems related to indoor contaminants.

The Committee notes that documentation of excessive indoor air pollution should not in itself be considered sufficient reason to relax standards for ambient air. The barriers between indoor air and outdoor air are not absolute, and ambient air contributes to indoor air. Furthermore, outdoor and indoor air pollutants may interact chemically and physiologically. The Committee recognizes the complexity of human exposures that have multiple sources. The development of effective and efficient strategies for mitigating hazardous contamination requires improved understanding of responses to exposure and of pollutant interactions.

The Committee has not attempted to set priorities for research on or regulation or control of indoor pollutants. Nor has it attempted to develop risk analyses for these pollutants. The order in which contaminants are presented in this report does not constitute a ranking of importance by the members of the Committee.

To set priorities for differentiating among indoor contaminants and to establish objectives for research and control programs, there must be a system for comparison. The dimensions of this system include the numbers of people exposed, the severity of exposures, and the consequences of the exposures. To be comprehensive, the system must also deal with ecologic and material damage, loss of productivity, degradation of artifacts, and other kinds of impact not related to health. Priorities could be derived from a ranking of these variables for pollutants of interest, but proper risk analysis would require measurement of exposures by population subgroups and weighting of exposure-response relationships by importance of outcome.

The Committee unanimously agreed that establishing firm priorities for research on indoor pollutants that ranks one contaminant as more important than another is premature. In most instances, we do not appreciate the extent of population exposures. Available reports on indoor air pollutants contain almost no data on the incidence of disease or even annoyance related to changes in pollutant

Chapter VI, on the measurement and monitoring of indoor pollution and exposure, reviews the design and components of indoor and personal monitors, mathematical models for estimating indoor pollutant concentrations, and methods of estimating total personal exposure.

Chapter VII, on the health effects of indoor pollution, relates the current understanding of the toxicologic and physiologic effects of specific contaminants that are found at high enough concentrations and in a broad enough range of indoor environments to constitute an actual or reasonably likely challenge to the occupants of those environments. In some cases, as in Chapter IV, the discussion is structured by source, such as involuntary smoking or indoor combustion products; the health effects may be attributable to specific components of a mixture of gases and particles, or it may be attributable to the general, mixed exposure. The chapter also considers indoor airborne contagion and allergens.

Chapter VIII, on the effects of indoor pollution on human welfare, covers a number of items related to comfort, productivity, and material protection in indoor environments.

Chapter IX, on the control of indoor pollution, emphasizes the engineering aspects of air-conditioning and indoor air-cleaning. Ventilation codes and standards are reviewed, and mechanical systems for conditioning and cleaning air are described. The chapter discusses strategies for controlling contaminants to maintain acceptable indoor air quality in general. Some pollutants, because of their sources or their physical and chemical properties, cannot be treated with conventional control systems, and strategies for controlling these pollutants are described specifically.

Appendix A lists national primary ambient-air quality standards and occupational-health standards (for the industrial environment) established for the United States. In addition, it lists indoor-air pollution standards and guidelines of several foreign countries. Ventilation standards for dwellings are also listed. This appendix is not exhaustive with respect to relevant pollution or ventilation standards, but it does offer a point of reference for some of the more commonly used standards.

Appendix B presents an example of the interactions among energy conservation, comfort, and indoor air pollution in a residence. This simulation exercise illustrates the tradeoffs among energy-cost savings, retrofit costs, and thermal comfort under the constraints of maintaining various hypothetical conditions of indoor air quality in a particular kind of single-family residence.

PRINCIPAL FINDINGS ON SPECIFIC POLLUTANTS AND CLASSES OF POLLUTANTS

RADON

Radon and its alpha-emitting decay products contribute a major portion of the biologically significant dose associated with natural background radiation. Many natural substances contain radium, a or deliberate disruption of asbestos-containing surfaces can result in increased fiber concentrations in the indoor environment. There have been a small number of studies in which fiber counts have been documented in association with normal building use. Extrapolation from what we currently understand about the exposure-response relationships for asbestos fibers to the very low concentrations reported in indoor spaces, such as schools, suggests a small health risk under conditions of normal use. However, deliberate modification of surfaces to remove asbestos from buildings may create a risk of exposure of occupants and workers. Buildings in which asbestos exposure is likely to occur can be identified. The risk of exposure from dislodged fibers can be reduced by containment. The occurrence of mesothelioma (a specific form of cancer believed to result only from the inhalation of asbestos fibers) may provide a very sensitive indicator of the exposure of the general population. Home exposure to asbestos due to aging, cracking, or physical disruption of insulated pipes or asbestos-containing ceiling tiles and spackling compounds may be greater than public exposures in schools, which have received the most attention. Homes built before 1950 in northern climates are more likely to have pipes insulated with asbestos plaster. Given the very common use of asbestos in homes, schools,and other buildings, there is a need for further assessment to identify structures where actual asbestos exposure constitutes substantial risk to humans.

original (an insignificant)

The extent of exposure of the general public to asbestos fibers has not been assessed; however, the occurrence of mesothelioma should be carefully monitored in the general population. Man-made fibers have produced skin irritation, but have not otherwise been demonstrated convincingly as hazardous to health. Epidemiologic and toxicologic investigation of synthetic fibers should continue. On the basis of present knowledge, synthetic fibers in the indoor environment should not cause undue concern.

TOBACCO SMOKE

Virtually every member of our society is exposed to tobacco smoke: 33% of the population smokes, and the rest are exposed to the smoke released by others. The constituents of tobacco smoke are well documented as hazardous, the prevalence of population exposures is very high, and there is an increased incidence of respiratory tract symptoms and functional decrements in children residing in homes with smokers, compared with those in homes without smokers. These considerations and recent evidence of increased lung-cancer rates among nonsmoking women living with smoking husbands have led us to conclude that indoor exposure to tobacco smoke has adverse effects. Coughing, headache, nausea, and irritation of eyes, nose, and throat are among the reported symptoms. Although many studies have measured various components of tobacco smoke indoors, total exposure has not been determined. Passive exposure to tobacco smoke may constitute an important exposure to respirable particles, such gaseous compounds as equipment at low load factors may decrease its overall combustion efficiency and increase emission of the products of combustion.

MICROORGANISMS AND ALLERGENS

Microorganisms are present in the indoor environment and are associated with human activity and the presence of domestic animals. The microorganisms include bacteria, viruses, and fungi. Many microorganisms—such as spores, molds, and fungi—multiply in the presence of increased humidity. It is possible that reduced ventilation and the increased use of untreated recirculating air could increase the concentrations of microorganisms. Many of these microorganisms can produce infection, disease, or allergic reactions. Respiratory viruses and bacteria can be transmitted from person to person in buildings and confined spaces. Certainly, respiratory infections are an important cause of morbidity that results in lost earnings and discomfort. It is reasonable to assume that some of the incidence of respiratory disease results from airborne transmission, but it is not at all clear what effect ventilation, air-conditioning, or air-cleaning will have on incidence. If the main transmission is between persons in contact with or close to each other, the mechanism and efficiency of disease transfer will be relatively insensitive to ventilation rates and other operating conditions of the air handling systems. However, to the extent that infectious and allergenic microorganisms remain viable and airborne, substantial reduction in ventilation rates will tend to increase concentrations and most likely the probability of infection and allergy.

MOISTURE

Water vapor in confined spaces is a product of metabolic and respiratory processes, as well as of indoor combustion and evaporation from clothes and dish-washing and bathroom functions. Condensation of water indoors has been shown to increase corrosive effects of absorbed gases. Decreases in ventilation tend to increase the indoor relative humidity during the heating seasons. Excess water vapor adsorbs or condenses on drier or colder surfaces, and that gives rise to increased deterioration or corrosion of building materials, furnishings, decorations, artwork, and other artifacts. Increased relative humidity may also promote the growth of molds, algae, and fungi. Thus, humidity control may become an important component of reduced-ventilation strategies. Some energy penalty may result that should be considered in relation to the energy savings that may be obtained through reduced ventilation.

RESPONSIBILITIES

The quality of the indoor environment is not the responsibility exclusively of any individual or government body. Even a single home

Studies explicitly addressing both long-term and episodic events have not been undertaken. Episodic release of contaminants in the indoor environment may be rare, but can lead to short-term high contaminant concentrations, which must be considered (in addition to long-term low concentrations) in assessing the overall health risk of indoor contaminants.

Measurement of indoor contaminants necessitates a sampling protocol that considers the spatial and temporal profile of several pollutants, as well as air diffusion and ventilation characteristics. In addition, measurement techniques for assessing indoor concentrations have to meet more rigorous requirements, particularly with regard to sensitivity and interferences. Unfortunately, many of the instruments required to characterize long-term and short-term indoor pollutant concentrations do not exist.

From a practical viewpoint, it would be desirable to determine the emission rate of an indoor pollutant by simple physical measurements and to infer the dose received by a human inhabiting the indoor space. But several intervening steps must be evaluated that involve degrees of uncertainty ranging from good estimates to total ignorance. The first process to be considered is the transport by diffusion and convection; transport is influenced initially by the fluid motion of the air near the source and throughout the indoor space. These modes of transport depend on a number of factors and are usually spatially and temporally variable. They lead to a concentration profile of the contaminant as a function of position and time. Measuring such profiles is virtually impossible, so the usual approach is to use mathematical models of dispersion. The human receptor is not stationary. Therefore, to obtain an exposure history, the spatial history of the receptor should be specified or estimated. Inexact knowledge of this function introduces a further degree of uncertainty. Dose to the receptor is related to exposure through deposition functions that express the fraction of the exposure that is available to reach specific receptor sites and produce effects. These deposition functions are themselves functions of several variables that are usually poorly specified or unknown. Thus, several layers of uncertainty are embedded between emission rate and receptor dose.

Indoor air pollutants generated or released indoors typically occur in concentrations and mixtures that are often episodic and generally vary over a wide range of time and from one space to another. As a result, human exposures are difficult to assess for individuals or groups. If, in addition, the adverse health effects are subtle, and especially if they are delayed, associations between indoor air pollutants and disease or premature mortality are unlikely to be discovered or demonstrated without a specific and substantial effort. Thus, efforts to improve indoor air quality most likely will have to be guided by information on the adverse health effects of pollutants demonstrated and studied in other settings, such as the occupational environment.

For a limited number of air contaminants that can be found in residential and public buildings, there is direct and circumstantial evidence that human exposures are large enough and common enough to control at reasonable cost, they can be supplemented or replaced by other engineering controls, such as dilution ventilation or air-cleaning. However, it should be recognized that the concentration reduction achieved through dilution may be less than that achievable with source control or air-cleaning, whereas the effectiveness of air-cleaning devices usually depends on frequent and effective application of maintenance procedures.

The specific source controls appropriate to each kind of contaminant can be expected to vary. For example, local exhaust control is most appropriate for nitrogen dioxide and carbon monoxide from gas ranges, the sealing of walls and floors for radon control, prohibition for asbestos-containing products, and specifications for care of furniture, drapery, and carpeting materials prepared with formaldehyde-containing substances.

Air-conditioning systems are generally designed to provide for all or most of the thermal environmental requirements (i.e., heating, cooling, and ventilating) of the occupied space. In the design of these systems, it is necessary to select components that will meet the particular requirements, such as heating coils or furnaces to meet winter design temperatures, evaporator coils and condensing units to meet summer design temperatures and humidities, and air-cleaners or ventilation air-flow rates to meet the air-quality requirements of the occupied space. The functional requirements of the space (i.e., residential, office, theater, etc.) also impose constraints on the type of system that might be selected. Because of the wide variety of functional requirements of indoor environments and the other constraints on design, a vast variety of control systems are used. For instance, lighting and acoustic requirements can influence the size and location of the air-conditioning system, the location of air supply and return devices, and air velocities in the air distribution system. Available information suggests that this trend will continue.

Although the requirements may be described discretely and some performance specifications are available for components of the system, the effectiveness of the system as a whole, including its impact on indoor air quality, must be evaluated. Unfortunately, very few data are available to indicate whether these systems, under actual loads, perform in accordance with their designs.

RECOMMENDATIONS

1. A staged assessment of the exposures of the general population to indoor pollutants and of the effects of such exposures on health and welfare should be conducted by the federal government in both residential and office buildings. Federal agencies with substantial interests in definition of the indoor exposures—i.e., the Environmental Protection Agency, the Department of Energy, the Consumer Product Safety Commission, the National Institute for Occupational Safety and Health, the Centers for Disease Control, the National Institute of Environmental Health Sciences, the Food and Drug Administration, the National Center for Toxicological Research, the

b. The effects of materials of construction and furnishings on indoor-pollutant content--specifically, there should be systematic evaluations of outgassing and surface attrition of particleboard and plywood (for formaldehyde and other organic substances); of wall and floor coverings and fabrics (for organic substances); of masonry products (for radon and dust); of wallboard, plaster, and spackling compounds (for dust and fibers); and of the materials used for heat storage in dry solar systems (for radon, dust, surface molds, etc.).

c. The differences in air distribution, diffusion, mixing, etc., associated with the use of different climate-control systems, such as forced-air, baseboard, and radiant floor or ceiling systems.

d. The effectiveness of air-cleaning systems in capturing pollutants in recirculating air--specifically, this will require in-place testing of systems, rather than test-stand evaluation of components, and the effectiveness of a variety of commonly used systems should be evaluated for radon and radon progeny, formaldehyde and solvent vapors, and cigarette smoke.

9. The potential for consumer products to contaminate the indoor environment needs to be evaluated. Hazardous components of these products must be identified and tested. Adequate labeling, warning users of hazards associated with product use and misuse in enclosed spaces, should be required. Testing in homes is needed to assess the extent of contamination, allergic reactions, and other health effects of pesticides, residues, and consumer products.

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I

INTRODUCTION

This report was prepared, at the request of the Environmental Protection Agency (EPA), by the Committee on Indoor Pollutants, which was appointed by the National Research Council in the Board on Toxicology and Environmental Health Hazards, Assembly of Life Sciences. It is intended to characterize the quality of the indoor environment, primarily with respect to airborne pollutants, and to determine the potential adverse health effects of indoor pollutants. The charge was to review, compile, and appraise the available knowledge. The Committee has also identified the research needed for abatement of indoor pollution. "Indoor" refers to the environments inside homes, schools, public buildings, and similar spaces to which the public has access; industrial working environments, however, are excluded from consideration here.

It is beyond the scope of this report to list all the pollutants found indoors that are hazardous to human health. The examples given make it plain that humans are exposed to a variety of potentially hazardous indoor pollutants from diverse sources. It is hoped that this report will encourage researchers to broaden the list of hazardous indoor pollutants and to characterize the hazards, so that the general public and those responsible for pollution control and abatement can be informed.

Throughout this report, pollutants are mentioned without discussion of their health effects. This does not constitute an oversight on the part of the Committee, but rather reflects a decision that the discussion here be adequate to show that there are indoor pollutants that cause adverse health effects in humans. The reader's attention is directed to Chapter III, which offers some recommendations for further health research with respect to these pollutants, for further exposure studies, and for public education about effective ways of reducing exposure to many contaminants encountered indoors.

Attention has recently been drawn to the problems of specific pollutants that originate indoors, e.g., formaldehyde released from urea-formaldehyde foam insulation and from urea-formaldehyde resins used to bind laminated-wood products, asbestos in building materials,

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Throughout the Committee's deliberations, and reflected in its conclusions and recommendations, were the following questions:

• Do indoor pollution exposures adversely affect the health, welfare, productivity, or sense of well-being of the population or any portion of the population?

• Does the indoor environment constitute an important component of exposure to pollutants?

• Are some groups or individuals at risk by virtue of high indoor concentrations of air pollutants or by virtue of susceptibility?

• What is known about the relative magnitudes of indoor and outdoor pollutant concentrations? Are the sources, ventilation rates, and reaction and removal factors that influence the indoor-outdoor relationships sufficiently well known to predict indoor concentrations and prescribe controls?

• What control strategies are effective for reducing population exposures to specific indoor pollutants?

• Will future changes in housing materials, products, ventilation codes, and activity patterns adversely affect health and welfare through changes in indoor exposures to air pollution?

It is very important that health and welfare problems related to indoor pollution be clearly differentiated from perceived problems or pseudoproblems. This requires measurements that are both accurate and sufficiently representative to identify or estimate the population at risk. And it requires that health research provide reasonable assurance that current or projected exposures can cause unacceptable effects in a portion of the population. Only when these two components are present can prudent judgments on recommended concentrations and control strategies be made.

Efforts to improve the public health and protect the public from hazardous airborne pollutants have been directed primarily toward improving the ambient and industrial environments. Improvements in outdoor (ambient) air have been achieved fundamentally through source control or removal; dilution by tall stacks and source relocation are not considered control strategies. In the indoor industrial environment, however, ventilation or dilution with outdoor air has usually proved to be the most cost-effective way of reducing worker exposure.

The indoor concentrations of airborne contaminants depend on five factors: the generation rate (for indoor-generated pollutants) or the ambient concentration (for outdoor-generated pollutants), the volume of the indoor environment, the air-exchange rate, the mixing efficiency of the indoor space, and the decay (removal) rates of the pollutants.

Until recently, the air in most buildings has been controlled for comfort and odor considerations, not for contaminants. Depending on heating, cooling, and humidity requirements for the indoor environment, the natural or forced infiltration of outdoor air to displace "conditioned" indoor air may entail a considerable energy penalty. Diluting the indoor air with outdoor air reduces pollutant exposures, indoor concentrations are relevant. Between 80% and 90% of an average person's day or year is spent in enclosed areas. On the average, people spend approximately 16 hours/day in their homes. And a rather consistent 1-2 hour/day is spent in transit. Thus, for at least some pollutants, the indoor concentrations are the most important, with respect to potential health effects or material damage.

The time-integrated exposure is perhaps important in determining chronic effects, such as corrosion. But the short-term peak or transient pollutant exposures may be more important, causing or contributing to both acute and chronic effects. Using the average amount of time a person is outdoors or indoors or the time-averaged concentrations may be misleading, if the concern is for peak-exposure effects. Peak exposures may occur indoors or outdoors. They may be encountered only during specific activities or in locations occupied only infrequently. In fact, short-term peak concentrations may contribute only a small proportion of a person's total time-integrated exposure. Both time-integrated concentrations and short-term, transient high concentrations must be considered, whether they occur indoors or outdoors.

Although the indoor and outdoor environments have not been sufficiently assessed to characterize all pollutant constituents comprehensively, it is useful to categorize indoor pollutants into three groups. Table I-1 groups pollutants by source. Those in the first group are principally of outdoor origin; thus, their concentrations are generally higher outdoors. This group includes sulfur dioxide; ozone; many elemental, inorganic, and organic species of particles; pollen; and some organic vapors. They are encountered indoors primarily because they are carried in with infiltrating air. Some may be carried indoors on surfaces. Once inside, particles can be resuspended, or organic substances may volatilize because temperatures and partial pressures are different. The higher indoor surface-to-volume ratios increase the removal rates of many of these pollutants.

Pollutants in the second group have both indoor and outdoor sources. Generally considered as belonging to this class are pollutants produced during combustion, such as carbon dioxide, carbon monoxide, nitrogen oxides, and some components of suspended particulate matter (primarily fine particles--diameter less than 3.0 µm). Because of the limited indoor mixing volume and longer residence times, concentrations of these and other combustion products often exceed outdoor concentrations. This group also includes organic vapors from solvents that can be used outdoors, as well as indoors. Biologic materials, such as fungal spores, have both indoor and outdoor sources. Fibers, including asbestos fibers, have indoor and outdoor sources. Serpentine rock, brake linings, and industrial facilities contribute asbestos fibers to the outdoor air. Insulation, fireproofing, and decorative materials used indoors may contain asbestos. Similarly, water vapor, sound, and nonionizing radiation can be considered to belong to this group.

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The third group of pollutants contains those whose sources are predominantly indoor. To this third group we may add pollutants whose concentrations are high enough only indoors to warrant concern for their effects. These pollutants are either generated by the occupants or associated with building materials, appliances, machines, consumer products, or art and craft materials. They include radon, formaldehyde, other organic substances from a variety of materials, asbestos and other fibers, odors, molds, and the numerous compounds identified in tobacco smoke.

Greater attention recently has been drawn to the third group of indoor pollutants. There have been reports of complaints about formaldehyde indoors after application of urea-formaldehyde foam insulation and particleboard and the installation of furnishings. Higher formaldehyde concentrations in European homes were reported in the early seventies. Radon and its progeny have been found in high concentrations in homes built on land reclaimed from phosphate mining and in other areas. Building materials, concrete, granite, and groundwater enriched in uranium are the apparent sources of radon. A plaster-resin material containing 10-30% asbestos has been used for fireproofing, acoustics, and, in some cases, decorative purposes. Asbestos concentrations above U.S. occupational concentrations occasionally have been found indoors.

The three general groups of contaminants found indoors are listed in Table I-1. Those in groups II and III are the prime focus of this report. Chapter IV discusses their sources and concentrations, and Chapter V, factors that affect indoor concentrations and personal exposures. The current understanding is reported with an illustrative but not exhaustive review of pertinent related work. Those two chapters discuss the relationships among sources, personal activity patterns, building factors, and ventilation that influence indoor concentrations and individual pollutant exposure. Temperature, light, and especially relative humidity also help to determine concentrations, chemical activity, and effects. Measurement of these effects to the point of predicting the ramifications of altering ventilation or introducing new products is not possible for all pollutants of interest, and in many cases the measurements have not been made. For other pollutants, the data will not be available until instruments are developed. For still others, the sources may be known, but their prevalence and distribution in buildings are not known.

Table I-2 summarizes some typical pollutant concentrations found in the indoor environment and compares them with outdoor concentrations. An indoor-to-outdoor ratio greater than 1 does not imply that hazardous concentrations occur indoors. This table shows that high concentrations of some pollutants have been reported in a variety of buildings that are commonly used during normal daily activities.

Water vapor is not reported in Table I-2 as a contaminant, but it is very important in the indoor environment. At low relative humidities, odors, particles, and such vapors as acrolein may be more irritating. Higher relative humidities favor mold and mite growth,

Table I-2 (contd)

Pollutant	Sources of Indoor Pollution	Possible Indoor Concentration[a]	I/O Concentration Ratio	Location
Asbestos	Fireproofing	<1 fiber/cc	1	Homes, schools, offices
Mineral and synthetic fibers	Products, cloth, rugs, wallboard	NA	—	Homes, schools, offices
Carbon dioxide	Combustion, humans, pets	3,000 ppm	>>1	Homes, schools, offices
Viable organisms	Humans, pets, rodents, insects, plants, fungi, humidifiers, air conditioners	NA	>1	Homes, hospitals, schools, offices, public facilities
Ozone	Electric arcing, UV light sources	20 ppb 200 ppb	<1 >1	Airplanes Offices

[a]Concentrations listed are only illustrative of those reported indoors. Both higher and lower concentrations have been measured. No averaging times are given. NA, not appropriate to list a concentration.

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other indoor contaminants, such as radon and asbestos, the direct health effects have been demonstrated in experimental animals and in occupational studies. And for still others, such as formaldehyde, information is from experimental conditions and anecdotal reports of complaints. That these noncriteria pollutants do or will cause harm through current or projected exposures of the general public has not been demonstrated by epidemiologic studies. Indeed, direct evidence from epidemiologic studies may not be forthcoming; epidemiologic studies would be compromised from the outset by uncertainties in indoor pollution concentrations and personal exposure. Nevertheless, if there is consistency of toxicologic and occupational evidence of the harmful nature of specific pollutants at the reported indoor concentrations, then there is reason for serious concern.

In the absence of a confirmed dose-response relationship, careful judgment is required. We should cautiously consider secondary consequences of conservation strategies to the indoor environment. Some pollutants may exert effects only at concentrations above a threshold; others may have no threshold. There may be synergism between pollutants or between pollutants and temperature, humidity, or disease organisms. Some pollutants may manifest effects subtly in behavioral changes. Others may have long latent periods between exposure and effects. In view of the uncertainty in the myriad potential outcomes, one fundamental relationship is clear: if, either deliberately or inadvertently, we systematically modify indoor environments by reducing ventilation or by increasing sources of indoor contaminants without ameliorating efforts, we will be increasing the population exposure to pollutants of indoor origin.

A review of indoor pollutant concentrations and possible health significance would not be complete without a discussion of the implications of these exposures for epidemiologic studies of ambient-air pollution. Several substances generated indoors are present in both indoor and outdoor air, including carbon monoxide, nitric oxide, nitrogen dioxide, and particulate matter. Recent investigations have confirmed that personal exposures to nitrogen dioxide and respirable particles are not well represented by ambient measurements if there are substantial indoor sources. For pollutants of outdoor origin, the evidence indicates that personal and indoor exposures are less severe than outdoor exposures.

These observations have implications for epidemiologic studies attempting to establish a relationship between ambient concentrations and health responses. Air-pollution epidemiology attempts to establish a statistical relationship between the dependent health variable and the independent variable of pollution exposure, correcting for other influential variables, such as age, sex, smoking, occupation, and socioeconomic factors. The air-pollution exposure most often chosen is derived from ambient monitoring appropriate to the study population. Leaving aside the question of spatial representation, consider the potential misclassification of exposure that may result from indoor pollution. Depending on study design and pollutant investigated, the results could overestimate, underestimate, or simply incorrectly estimate the relationship between air-pollution

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TABLE I-3

Possible Consequences of Indoor Air Pollution in Epidemiology

Type of Pollution	Source of Bias	Result of Bias
Outdoor pollutant--indoor concentration lower than outdoor; air-conditioning causes further reduction (ozone, sulfur dioxide)	Systematic bias--air-conditioned homes not uniformly distributed	Overstated relationship: if studied (polluted) population has no air-conditioning, this overstates relationship between outdoor pollutant and health effect
		Understated relationship: if studied (polluted) population has more air-conditioning than other population, relationship between pollutant and health effects will be understated
	Random bias--distribution of air-conditioned homes not known	Underestimated relationship: effect of pollutant on health will be understated because unknown number of people have reduced exposure
		Increased error of estimate
Indoor pollutant--indoor concentration higher than outdoor (nitrogen dioxide, respirable particles)	Systematic bias--gas-cooking homes not randomly distributed	Overstated relationship: if gas-cooking homes are found mostly in studied (polluted) area, this will overstate effect of outdoor pollutant
		Incorrect relationship: if different pollutants are studied and outcome health variable is influenced by indoor pollutant concentrations, effect may be understated or not detected and attributed to wrong pollutant
		Increased power: if distribution of indoor air pollution sources or ventilation factors are known, analysis is stratified by exposure and statistical power to measure effects may increase
		Understated relationship: if gas-cooking homes are found mostly in clean area, effect of outdoor concentration will be understated

II

SUMMARY AND CONCLUSIONS

CHARACTERIZATION OF INDOOR AIR POLLUTION

The air quality of the indoor environment has been characterized in a limited number of pilot studies. Because of the large variety of distinct indoor environments--single and multifamily residences, offices, hospitals, restaurants, schools, recreational facilities, transportation facilities, etc.--there is a major difficulty in characterizing "the indoor air environment." Moreover, even within one indoor environment differences in structure, in the operation and strength of emission sources, and in human activities add to the complexity of characterizing air quality. The available data, mostly from the residential environment, amply demonstrate the diversity of characteristics of indoor air and help in identifying subjects that warrant further research.

RADIOACTIVITY (pp. IV-2--IV-26)

The data base on sources and source strengths of indoor radon is just beginning to be established. Initial attention focused on building materials and groundwater. Recent evidence from regional studies in the United States points to ground soils (under buildings) as perhaps the major source of radon. Only a small number of buildings in the United States have been measured for radon and radon progeny. Indoor concentrations are affected by various factors, including ventilation rate, deposition of radon progeny on indoor surfaces, and interactions of radon progeny with fine particles from various sources (e.g., tobacco smoke and house dust).

Data from several studies indicate that indoor radon-222 concentrations vary by at least two orders of magnitude, with average values of about 1 nCi/m^3. Such a large range is not surprising, inasmuch as the studies included various types of buildings, building materials, underlying materials, and ventilation rates and used many different measurement techniques. Radon progeny concentrations are often given as potential alpha-energy concentrations (PAEC), expressed force. Most contamination is episodic, activity-related, and local. Fiber counts and mass concentrations of fibers have been measured and shown to exceed those outdoors, and on occasion they may approximate the occupational limit of 2 fibers per cubic centimeter. Fortunately, during normal use, buildings containing asbestos have not shown indoor fiber counts higher than outdoor counts. Current data are very limited and apply mostly to schools and a few office buildings, but it appears that the general public exposure to asbestos fibers is exceedingly low in public buildings. A systematic and comprehensive survey of indoor asbestos fiber contamination is needed and will require reliable, portable, and continuous monitors. Asbestos control technologies have been applied in various indoor environments. Asbestos removal requires a complex protocol to be carefully applied, because the very activity of removal may cause severe asbestos contamination.

INDOOR COMBUSTION (pp. IV-78--IV-112)

Unvented combustion appliances, especially gas stoves, are major sources of indoor air pollution. Although emission rates from a small number of gas stoves have been determined for several pollutants, the data base is very limited. Indoor concentrations of carbon monoxide and nitrogen dioxide associated with incomplete combustion have been observed to exceed current ambient-air quality standards. Carbon dioxide emission from unvented combustion appliances may build up to concentrations in the range of occupational air quality standards. Local exhaust ventilation appears to be the most effective control strategy for reducing pollutants from combustion. Improved combustion efficiency and source elimination (i.e., adsorbers or a change to the use of electric ranges) are two additional control approaches. Residential wood and coal stoves are also potential sources of indoor contamination. Attached and underground garages can contribute to indoor carbon monoxide, nitrogen dioxide, and particle concentrations.

Carbon Monoxide

Indoor carbon monoxide concentrations are often higher than corresponding outdoor concentrations. High indoor concentrations may be attributed to emission from such sources as gas cooking facilities, attached garages, faulty furnaces, and cigarette-smoking. Typical average indoor carbon monoxide concentrations in residences vary between 0.5 and 5 ppm; observed peak values reach 25 ppm. In public buildings, the indoor concentrations are usually lower than observed residential concentrations, except under conditions of exceptionally heavy smoking, as in bars, or in office buildings with underground garages and improperly designed or malfunctioning HVAC systems.

Concentrations of fine particles (diameter, less than 2.5 μm) range from 10 to more than 260 μg/m^3 for a 24-h sample. The higher concentrations are almost always associated with smoking. Concentrations in bars, offices, and cars with smoking can be higher than 500 μg/m^3.

ODORS (pp. IV-112--IV-147)

Odors arising from occupants and their activities figure in indoor-air quality issues predominantly on the basis of comfort, rather than health. Such routine indoor activities as cooking, smoking, bathroom use, and maintenance give rise to odors that are often disagreeable and in some cases offensive. To a varying degree, almost all building materials and furnishings are sources of odor. The determination of odor attributes--such as intensity, character (pleasantness/unpleasantness), duration, and perceptual threshold--is complex, but can be effectively accomplished with a combination of instrumentation and the use of panels of human observers. Odor controls increase in complexity from good housekeeping to ventilation to masking and, finally, to air-cleaning.

OTHER CHEMICAL POLLUTANTS (pp. IV-26--IV-55, IV-78--IV-93)

Nonmethane Hydrocarbon

The ratio of indoor to outdoor total nonmethane hydrocarbon (NMHC) concentrations is greater than 1 for about 90% of the total monitored hours; that is, the NMHC concentrations observed in the residential environment are almost always higher than the outdoor concentrations. Fluctuations in the indoor concentrations may be associated with cooking, cleaning, and other activities. Typical concentrations in residential buildings vary between 0 and 8.0 ppm, whereas typical outdoor concentrations are between 0 and 3.5 ppm. Measured NMHC concentrations in new office buildings often exceed 10 ppm and reach as high as 50 ppm; this may be attributed to the extensive use of synthetic organic building materials and furnishings in new office buildings, as well as cleaning solvents and maintenance materials.

Ozone

Indoor ozone concentrations are generally lower than outdoor. Unless there is an indoor generation source of ozone from electric arcing or ultraviolet radiation (such as an electrostatic precipitator or a document copier), the ratio of corresponding hourly indoor to outdoor concentrations is almost always less than 1. Ozone is primarily a product of outdoor photochemical reactions. Precursor pollutants leading to the formation of ozone are primarily of automotive origin, but other sources include the combustion of fuels notably bacteria and fungi—also play important roles in the deterioration of surfaces and spoilage of stored materials.

MONITORING AND MODELING OF INDOOR POLLUTION

Indoor air quality monitoring, in addition to pollutant sampling, must involve ventilation-rate measurements and daily activity logs of occupants. In addition, meteorologic data and outdoor pollution measurements may also be needed for the monitoring and assessment of indoor pollution.

Most indoor monitoring studies have relied on instrumentation developed for monitoring workplace or ambient air. The use of conventional monitoring instrumentation is frequently awkward, expensive, and suitable only for a limited number of comprehensive indoor air quality studies. Owing to the special requirements, instruments and sampling strategies are being developed specifically for indoor residential and office environments. The advent of personal monitors has permitted, in a few cases, the startup of monitoring and exposure studies for specific pollutants—nitrogen dioxide and radon. Personal and portable monitors are being developed for carbon monoxide, formaldehyde, and particulate matter. Monitoring the indoor environment, either with fixed-location sampling devices or with personal monitors, requires special protocols addressing pollutant sampling, instrument calibration, source operations, and occupant activity. When indoor monitoring takes place under normal occupancy conditions, the protocol must ensure that the act of monitoring itself avoids influencing those occupancy conditions.

Indoor-air pollution simulation models provide a theoretical framework for relating outdoor pollutant concentrations, meteorologic factors, building factors, ventilation rates, and indoor source and sink dimensions with indoor pollutant concentrations. Most importantly, a validated simulation model must accurately predict a desired concentration for conditions other than those tested experimentally. Depending on ventilation conditions and the geometry of the structure, a single room, a floor, or a whole building may be adequately approximated as a single air-quality compartment (entity). However, if sources and sinks are not uniformly distributed and if the indoor environment is large, pollutant stratification occurs within a building and a multicompartment numerical model is required to simulate the indoor-air pollution concentrations. Almost all numerical models are mass-balance equations that simulate the dynamic relationships among indoor pollutant concentrations, outdoor concentrations, indoor sources, and sinks (including ventilation).

FACTORS THAT AFFECT EXPOSURE TO INDOOR POLLUTION

Exposure is a dynamic concept that is defined as the joint occurrence of two perhaps independent events: the presence of a person in a specific environment and the presence of a pollutant at a specific

INVOLUNTARY SMOKING (pp. VII-63--VII-81)

Tobacco smoke is a major source of both gaseous and particulate pollution in the indoor environment, and the nonsmoker absorbs measurable amounts of carbon monoxide and nicotine, as well as small amounts of other smoke constituents, owing to involuntary smoking. The carbon monoxide absorbed varies from negligible in well-ventilated office buildings to amounts that raise the carboxyhemoglobin (COHb) concentration by 2-3% in an exposure of 1-2 h.

The COHb produced by the most severe involuntary-smoking exposure likely to occur in everyday living is capable of reducing the maximal exercise capacity of normal healthy adults, but does not measurably affect submaximal exercise capacity. Carbon monoxide has been shown in one study to reduce the amount of exercise that patients with hypoxic chronic obstructive lung disease can perform before the onset of dyspnea.

Patients with angina pectoris have a reduced exercise tolerance after involuntary smoking that may be a combination of psychologic stress and a carbon monoxide-induced decrease in oxygen delivery to the myocardium. Carbon monoxide clearly reduces the amount of exercise possible before the onset of angina in patients with angina pectoris.

Small changes in visual and auditory vigilance have been demonstrated at COHb concentrations that can be produced by involuntary smoking, but no change in tests of complex function has been demonstrated. Involuntary smoking has not been shown to produce acute changes in lung volumes or in a number of small-airway resistance measurements in normal healthy adults. Long-term exposure to cigarette smoke has been related to small-airway dysfunction in healthy nonsmoking adults.

Children whose parents smoke have been shown in some studies to be more likely to have respiratory symptoms, bronchitis, and pneumonia as infants. This relationship has been found in some studies to be independent of parental symptoms, socioeconomic class, and the smoking habits of other children in the household. It shows, in those studies, a dose-response relationship with the number of cigarettes smoked per day by the parents. To the extent that these associations may be due to cigarette smoke, it is reasonable to assume that the particle mass or a specific compound contained therein, rather than nitrogen dioxide or carbon monoxide, is responsible.

A twofold risk of cancer mortality in nonsmoking women has been associated (in a Japanese study) with having husbands who smoke. Apparently, the risk is proportional to the amount of passive smoking.

RADON AND RADON PROGENY (pp. VII-6--VII-21)

The radon gas that diffuses out of radium-bearing building materials, subsurface soil beneath buildings, and well water into the indoor air undergoes radioactive decay. As a result, the indoor air contains both radon gas and alpha-emitting decay nuclides in particulate form, herein referred to as "radon progeny."

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Fibrous materials used as substitutes for asbestos include glass fiber, rock wool, and slag wool. They have been shown, in animal injection and implantation studies, to be capable of producing lung fibrosis and mesothelioma. However, they are much less important in this regard than asbestos, and there is no corresponding human-health evidence associated with the forms in which they are used in industrial and consumer products. Thus, their substitution for asbestos appears to be beneficial, inasmuch as such substitution reduces the risk associated with asbestos exposure.

<u>FORMALDEHYDE</u> (pp. VII-21—VII-37)

Formaldehyde has been the subject of numerous complaints regarding irritation of the eyes and respiratory tract, nausea, headache, rash, tiredness, and thirst. These symptoms have been reported mainly by residents of mobile and conventional homes in which formaldehyde-yielding products have been identified. Documented cases of bronchial asthma due specifically to formaldehyde are few; more commonly, asthma is aggravated by the irritating properties of formaldehyde.

Aqueous solutions of formaldehyde damage the eye and irritate the skin on direct contact. Repeated exposure to dilute solutions may lead to allergic contact dermatitis. Poisoning from ingestion is uncommon, because the irritancy of formaldehyde makes ingestion unlikely.

A preliminary report from the Chemical Industry Institute of Toxicology has shown that formaldehyde induces nasal cancer in laboratory rats and in some of the laboratory mice similarly exposed at the high dose. Nasal cancer has developed in the group of rats exposed at 15 ppm and 6 ppm, and dose-related histologic changes of the nasal mucosa in rats exposed at 2 and 6 ppm. Although the human mutagenic and teratogenic potential of formaldehyde is not known, it has exhibited mutagenic activity in a wide variety of organisms.

Data on the health effects of other environmental factors and their interactions—such as cigarette-smoking history, variability of health status, age, and genetic predisposition (which may modify responses to formaldehyde)—have not been adequately evaluated. That makes it difficult to assess accurately the health risks attributable to exposure to formaldehyde. However, the complaints of residents of homes with formaldehyde-containing products are similar to complaints made by persons studied in the laboratory at similar formaldehyde concentrations; hence, these health complaints may be related to formaldehyde exposure in the home. Accordingly, a substantial proportion of the U.S. population may be likely to develop symptoms as a result of exposure to formaldehyde at low concentrations. It has been estimated, on the basis of laboratory tests and various kinds of population surveys, that perhaps 10-20% of the general population may be susceptible to the irritant properties of formaldehyde at extremely low concentrations. For example, some persons report mild eye, nose, and throat irritation and other symptoms at concentrations less than 0.5 ppm, and some note symptoms at concentrations as low as 0.25 ppm.

INDOOR AGENTS OF CONTAGION AND ALLERGY (pp. VII-81—VII-116)

There is considerable evidence that a number of contagious-disease organisms--including those associated with influenza, Legionnaires' disease, tuberculosis, measles, mumps, and chicken pox--are capable of airborne transmission in the indoor environment. Other respiratory diseases, such as the common cold and pulmonary infections, involve airborne transmission. Because of the important role of respiratory diseases in overall acute morbidity, airborne transmission of contagious agents is important in the indoor environment.

The droplet-nucleus theory--whereby liquid particles emitted from the human respiratory tract evaporate to a particle size that can remain airborne for a period sufficient to be carried by natural air currents or convective ventilation flows and later deposited in the human airways--is generally accepted and used as a basis for transmission models. The effect of reduced ventilation in residences and offices on the incidence of infections is unknown.

Only a few airborne allergens are found in enclosed spaces. Their health effects are difficult to estimate, although their impact is sometimes appreciable.

EFFECTS OF INDOOR POLLUTION ON HUMAN WELFARE

Effects on human welfare are taken to include loss of productivity, human discomfort, and effects on materials, primarily soiling and corrosion of exposed surfaces.

SOCIOECONOMIC STATUS (pp. VIII-1--VIII-3)

Members of low income classes are more likely to live in poorly insulated housing with higher air-exchange rates. Several reports have indicated that gas stoves or unvented gas or kerosene heaters are used for supplemental space-heating in northern cities. The percentage of homes with smokers appears to be inversely related to parental educational level. Lead intoxication in children occurs disproportionately in lower-income urban populations; higher ambient airborne-lead concentrations may contribute. However, some potential sources of indoor pollution may occur more frequently in the middle and upper income brackets. Many consumer products, as well as coal and wood stoves, exemplify such sources. Although the distributions of these and other factors may be functions of socioeconomic status that cause some segments of society to be more or less disadvantaged with respect to a hazardous indoor environment, the available data allow little more than speculation.

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CODES AND STANDARDS (pp. IX-2--IX-16; Appendix A)

Minimal requirements of acceptability are often stated in building codes and standards in terms of air-exchange rules, temperature limits, and so forth. These documents tend to cause minimal requirements to be established for such direct effects as temperature, humidity, and odors, but may not be sufficient to provide for other effects, such as air pollution or noise. Nor do these codes consider the interactions that can occur among these factors and other system features such as lighting, thermal load, and spatial requirements.

AIR DIFFUSION CONTROL (pp. IX-16--IX-22)

Indoor air quality is most commonly controlled by forced-air systems. However, if diffusion control is designed without considering possible stratification of air within a room or a building, there may be local violations of thermal, humidity, or air-quality criteria for acceptability, and occupants may be exposed to conditions other than expected from the design.

INDOOR ENVIRONMENTAL CONTROL SYSTEMS (pp. IX-16--IX-22)

Control methods for indoor environments require specification of environmental criteria and definition of the control variables. The environmental criteria that are identified in this document are health, comfort, welfare, energy consumption, and costs. The control variables identified are spatial requirements, lighting factors, thermal factors, air quality, and acoustic factors. Although environmental criteria and control variables can be identified and described, the capability of sensing the appropriate variables and controlling the system to meet the specified criteria is severely limited. Moreover, most indoor environmental control systems must attempt to respond activity or passively to all five of the control variables simultaneously.

Residential air-conditioning systems are conventionally designed to respond to spatial, thermal, and air-quality variables and, to a limited extent, acoustic variables. For larger facilities, such as offices and schools, air-conditioning systems must also respond to variations in occupancy and lighting loads, in addition to spatial, thermal, air-quality, and acoustic factors. For other functional spaces (e.g., concert auditoriums, art galleries, museums, and hospitals), some or all of the variables must be controlled with additional precision.

For many years, air-conditioning systems were designed to meet the required environmental criteria (primarily thermal) at minimal first cost. Operating costs were not considered important as first costs, because energy was relatively inexpensive, compared with labor and material. However, as the costs of energy increased rapidly during the last decade, operating costs became a major factor in environmental control. Energy-conservation measures were implemented in many

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III

RECOMMENDATIONS

The Committee on Indoor Pollutants recognizes that decisions affecting the quality of the indoor environment are being made by manufacturers, government agencies, builders, building operators, professional organizations, and private individuals. The decisions encompass a broad range of activities in our society, with important and long-term consequences. Federal agencies are planning energy-conservation programs in buildings, contemplating the banning of some products, and estimating the health risk associated with indoor pollutant exposures. State and local government units are considering revisions of building codes, ordinances to prohibit smoking in public buildings, and requirements that asbestos insulation be removed from schools. It can be presumed that there are similar examples of decision-making at various levels in the private sector that affect indoor environmental quality. In view of the possible impact of these decisions, the Committee is concerned that policy, research, and economic decisions be formulated with proper understanding of their implications for the quality of the indoor environment. For specific indoor contaminants, two basic inadequacies in the available data must be resolved rapidly: poor definition of population exposures and lack of understanding of the health and welfare consequences of exposure to contaminants in the indoor environment. This chapter presents the Committee's general and specific recommendations for remedying these inadequacies.

We have observed that the existing data base is, for the most part, derived from pilot studies or anecdotal reports. The results of the pilot studies reveal the complexity and diversity of the information that must be looked at in evaluating the quality of indoor environments. In some cases, the potential health significance of exposure to indoor contaminants has been alluded to; but the full extent of a potential problem with respect to types of contaminants, concentrations, and numbers of people exposed has not been determined.

We believe that the research problem is large and requires national coordination. A national coordinated research program would have the following advantages:

effects and recommends the development of model strategies (for sampling, etc.) or protocols as guidance for future research. (The formulation of model sampling strategies, for example, is not meant to stifle innovation in sampling designs, but rather to establish the model to be used for comparing data obtained by researchers whose objectives differ.) The Committee recommends the formulation of strategies and protocols for measuring the strength of various indoor pollutant-emitting sources and for assessing the effectiveness of control devices and procedures in abating pollution.

The Committee recommends the formulation of a standard format for reporting data and the development of protocols for standardized statistical approaches that will require only minimal analysis to be used in validating numerical models. These would help to reduce difficulties in comparing existing data and facilitate the development of valid conclusions; conclusions now are often based on exceedingly small samples.

Even comprehensive information about the quality of the indoor environment would not permit determination of total pollutant exposure. It must be recognized that people are exposed to many of the same pollutants outdoors, in transit, in the occupational-industrial environment, and elsewhere. The relative importance of each kind of environment can be established and priorities can be set if and only if pollution exposures in all distinct environments are characterized. Lack of a complete assessment may lead to inefficient allocation of scientific effort and control funds in each kind of environment. The Committee believes that the research efforts to characterize indoor air pollution and human exposures indoors must continue and intensify, if we are to determine total human exposure to pollutants and understand environmental contamination and its effects on health and the quality of life.

The remainder of this chapter presents specific recommendations for research, grouped by class of indoor contaminant discussed in the body of the report, and discusses the need for increased understanding of indoor pollutants in general and the need for consumer protection.

RADON

Nationally coordinated investigations on radon and its progeny should take place on two levels. A well-funded and coordinated national survey of radon concentrations in a representative sample of residential buildings is necessary to estimate the exposure of the total population to radon and radon progeny. Monitors that use the track-etch plastic chip may be adequate for integrated measurements for such national surveys, because they are inexpensive and are specific to radon. However, the performance of these and other passive devices needs to be carefully evaluated. Inexpensive instruments for measuring radon concentrations on a short-term basis need to be developed. These instruments should be available to local health agencies and others for spot surveys. On another level, research on the transport and transformation of radon inside buildings

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Some of this emission occurs over long periods. Thus, long-term effects in humans continuously exposed to formaldehyde at low concentrations need to be studied. There is a particular need to assess the carcinogenic potential in the concentration ranges of human exposures, inasmuch as one study in one strain each of rats and mice has shown that long-term exposure (lasting 24 mo) caused nasal cancer. Humans have been and are now being exposed to formaldehyde in several types of occupations and in a variety of structures. Epidemiologic investigations are needed to assess the human health effects of formaldehyde, the magnitude and duration of exposure, and the influence of cigarette-smoking habits and the presence of other contaminants. The mutagenic, embryotoxic, and teratogenic effects must be included in the epidemiologic and animal studies. In humans exposed to formaldehyde, the mechanisms of airway and target cell responses must be evaluated and characterized as to sensitization and adverse effects in susceptible population groups, such as asthmatics and persons with chronic obstructive lung disease. Exposure-effect relations and the mechanisms involved in the biologic effects require further animal toxicologic research. Formaldehyde should be restricted to the extent that household consumer products and building products in normal use will not release potentially hazardous or irritating amounts of formaldehyde into indoor air.

TOBACCO SMOKE

Tobacco smoke has shown some evidence of being a major contaminant in many indoor environments. Involuntary exposure to tobacco smoke should be assessed to identify locations and populations with high exposure and to determine the factors that contribute to high exposures indoors. Physical and biologic evaluation of tobacco-smoke constituents should be continued. Tobacco-smoke constituents should be tested for their toxic effects, their ability to act as mutagens or promoters of carcinogenesis, and their effects in combination with other indoor pollutants. In addition, such properties of tobacco smoke as mass and age, chemical composition, irritation factors, and odor components should be examined to learn how they are affected by ventilation rate, occupancy, extent of smoking, air-cleaning, and other control strategies.

The extent to which passive exposure to sidestream tobacco smoke produces respiratory tract symptoms and functional decrements in nonsmokers, especially children, needs further documentation and measurement. Prospective studies of children in homes with smokers would be especially desirable to determine rates of lung maturation and illness frequency during childhood and adolescence.

Information on the potential health effects of exposure of nonsmokers to tobacco smoke should be widely disseminated. The "energy-cost penalty" of providing adequate ventilation in indoor environments that permit smoking should be analyzed in a variety of public buildings. Increased cigarette taxation as a mechanism of studies should determine the population exposure to nitrogen dioxide over both the short and the long term. In addition, the applicability of ambient-air fixed-location monitors for recording nitrogen dioxide and carbon monoxide concentrations indoors and for assessing individual exposures should be studied.

Chemical reactions and rates of removal of emitted gases should be determined. Nitrogen dioxide formation and removal should be examined in detail. This will involve the simultaneous measurement of other gaseous compounds. The effects of reduced air-exchange rates, zone ventilation, and source modification on pollutant reactions should be assessed. As with other indoor contaminants, there is a general need to improve instrumentation. Both nitrogen dioxide and carbon monoxide monitors are available for passive integrating sampling and for continuous monitoring. However, for indoor use, they need to be evaluated with respect to interferences. To evaluate short-term personal exposures, lightweight continuous monitors for oxides of nitrogen need to be developed. Evaluation of personal exposures to respirable particles is currently limited to integrated samples. Lightweight portable samplers or direct-reading monitors that can measure mass concentration over shorter periods are needed.

Nitrosamines can be formed during cooking and smoking. However, very few detailed investigations of the concentrations, mechanisms of formation, and potential control methods have been done.

The polynuclear aromatic hydrocarbons can be formed during high-temperature combustion of organic matter. Some of them have been found indoors as a result of emission from self-cleaning ovens and fireplaces. Pilot studies should be initiated to evaluate the extent of emission of polynuclear aromatic hydrocarbons and their indoor concentrations.

The magnitude and prevalence of decreases in pulmonary function and increases in respiratory tract infection rates among children living in homes with gas ranges and homes with electric ranges need to be determined more accurately, and there are several related issues that require clarification:

- Whether the effects are due entirely to the increased nitrogen dioxide concentration in the gas-stove homes or are influenced by the presence of other combustion effluents from the stoves, such as carbon monoxide, formaldehyde, and particles.
- Whether the effects can be related more closely to peak concentrations or to long-term average exposures.
- Whether the effects of exposures to sidestream cigarette smoke and to nitrogen dioxide are additive or synergistic.
- Whether exposure-response relationships can be developed and, if so, whether they indicate an effective threshold concentration for peak or average exposures.

The influence of reductions in air infiltration rates in existing buildings on indoor concentrations of combustion products needs to be determined. Among the potentially serious health consequences of reductions in infiltration are:

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AEROPATHOGENS AND ALLERGENS

Little is known about the sources, concentrations, and survival rates of many aeropathogens in homes and other buildings. Relationships among the incidence of respiratory infections, concentrations of aeropathogens, and air-exchange rates in buildings must be examined. The urgency arises from the recent modifications in building ventilation codes that recommend reduced ventilation rates in residential and commercial structures. A sample of commercial, institutional, and residential buildings should be evaluated for the types and concentrations of aeropathogens under a variety of conditions of occupancy, human activity, ventilation, humidity, temperature, and contaminant control. Special attention should be given to the newer energy-efficient buildings and buildings with drastically reduced ventilation. The potential for infectious contamination from air-cleaning filters, air heat-exchangers, air humidifying systems, and air-conditioning systems deserves special attention.

Other agents in the indoor environment known to produce allergic responses include pollens, household mites, molds, animal dander and excreta, and bacterial spores. Further work is needed to characterize the size distribution of allergen aerosols, their sources, and the conditions that are conducive to their generation. The airborne concentration of allergens in the indoor environment has been determined in only a few instances, and the relationship between indoor concentration and response is poorly understood. Case-control epidemiologic and immunologic studies are needed to clarify exposure-effect relationships. Such studies will require improved instrumental and analytic techniques to facilitate characterization of concentrations of allergens and of the variety of microorganisms in the indoor environment. Synergism of biologic and nonbiologic agents should be explored in animal toxicology studies.

Some acute allergic responses, such as "humidifier fever," are of unknown etiology. The pathologic agents in immunologic and case-control epidemiologic studies need to be identified. The pathogenic process by which repeated small exposures to some allergens often lead to irreversible fibrotic lesions, as in bird-fancier's disease, should be elucidated, and the potential of other, more common indoor pollutants to produce such disease states should be evaluated.

VENTILATION STANDARDS AND CONTROL STRATEGIES

Knowledge of ventilation rates is of primary importance in studies of indoor contaminant concentrations. Given the variety of residential living units and other public and private facilities, it is not surprising that very little information exists to characterize air-exchange rates. Studies should begin to characterize air-exchange rates in existing buildings by building type, geographic location, occupant life styles, building operation, and observed average pollutant concentrations during the different seasons. Smaller-scale activity-related concentration data will eventually advance our knowledge of pollutant exposure. This knowledge is a prerequisite to rational allocation of resources for warranted reductions in population exposures.

The Committee urges investigation in the behavioral aspects of indoor environments, specifically the relationships among performance, sense of well-being, contaminant concentrations, and stress. Temperatures, odors, and noise outside preferred ranges can reduce productivity, especially in self-pacing tasks. The relationship between productivity and the quality of the indoor environment needs to be determined. It is recognized that relationships between the behavioral variables and pollutant concentrations may be difficult to establish. Simultaneous measurements of trace organic vapors, water-vapor content, conductivity, noise, light, temperature, and air exchange rates should be pursued.

EDUCATION

Public education offers an effective way of reducing exposure of the population to many contaminants encountered indoors. People informed about the potential for exposure to pollutants from consumer products, tobacco smoke, combustion products, etc., will exercise some control to reduce the pollutant concentrations in their environments. For the most part, their options for controlling these pollutants are limited to source maintenance, ventilation control, and, to some extent, air-cleaning. Information about maintaining a clean indoor environment and assessing indoor spaces for potential contamination before purchasing or renting a structure and a variety of suggestions could be disseminated through health-maintenance organizations, regional health-planning agencies, public-affairs offices, the Environmental Protection Agency, the Department of Housing and Urban Development, the Department of Energy, the Consumer Product Safety Commission, and a variety of other federal and state agencies. The General Services Administration, the armed forces, and the Department of Housing and Urban Development are responsible for many residences and other buildings. Through certification of minimal acceptable occupancy standards, these federal organizations could develop strategies to ensure that indoor spaces under their jurisdiction are free from hazardous concentrations of contaminants.

Professional and trade associations could be instrumental in developing and disseminating information. These associations are encouraged to establish standards for acceptable practice, with respect to manufacturing, designing, building, and using products, equipment, and structures that influence the quality of the indoor air.