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The Status of Indoor Air Pollution

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Indoor air pollution, specifically restricted in its meaning to chemicals in home indoor air environment, presents a new and probably an important challenge to the researchers of the air pollution field. The general overview of this topic suggests that the voluminous data generated in the past ten or so years have only defined the rudiments of the problem, and significant areas of research still exist. Among the important areas where information is lacking, the exposures to contaminants generated by the use of consumer products and through hobbies and crafts represent perhaps the most urgent need for substantial research.

Introduction

One of the consequences of any human activity is the release of chemicals into the air. This statement suggests that indoor pollution is neither new nor likely to be very significantly worse than it has been all along in history.

Until very recently, "polluted air" was associated with the air contaminants of industrial workplaces and with the air of major cities. In fact, almost all of the rigorous data on the health effects of air contaminants arise from occupational exposures or major air pollution episodes where the exposure levels were near the occupational exposure levels. It is also true that, until very recently, a sufficiently high number of large cities and industrial areas had perceptible daily air pollution levels considerably worse than what we consider to be very poor air quality today. The popular perceptions of dirty air, and undeniably observed health effects in the occupational environment, justifiably led to the restriction of the definition of "polluted air" to these two categories.

The relentless search for elusive answers with respect to the health effects of outdoor air pollution generated an impressive accumulation of data. Unfortunately, until recently, the concrete evidence of health effects seemed to hinge on slightly varied analysis of the same air pollution episodes over and over again. About twenty years ago, the observation—which is obvious in retrospect—that the population tends to spend more time indoors than outdoors (or perhaps frustration with analyzing London and Donora data for the *n*th time) led to at first very scant and later ever increasing concern and investigation of nonoccupational air environments. Even the earliest measurements suggest that the quality of air indoors might be just as important as the quality of air outdoors (*1*).

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In the past decade, much has been learned, but as yet we have barely scratched the surface. This paper is devoted to the definition of the problem, an outline of the complexities involved, and the challenges facing the researchers. Since a short treatise will not do justice to the amount of information available, specific values, results and conclusions will be summarized as concisely as possible so that it will be easier to focus on what is not known.

The data hitherto gathered suggest that the air pollution levels encountered outdoors will not have a significant effect on healthy adults. All indications point out that the population at risk comprises the young, the elderly, and the infirm. It is a valid assumption to state that these highest risk groups spend a much higher portion of time indoors than the general population. This points out an important consideration that the highest risk groups are exposed to the outdoor air pollutants at best in a secondary manner and more importantly, they are exposed to pollutants generated in a confined environment which may be retained for longer periods of time in a relatively undiluted form. Consequently, it is possible to summarize the important parameters of indoor pollution in several distinct categories: (1) lifestyle variables, (2) indoor habitat variables, (3) contaminant sources, and (4) contaminant classes and levels.

For simplicity, indoor environment will be defined as home environment, and, with few exceptions, other indoor environments will not be considered to be within the scope of this paper. An air contaminant by normally accepted definition, may be a chemical or physical entity. The physical indoor air contaminants include ionizing and nonionizing radiation. In a very general sense, the problems associated with the physical contaminants are very similar to those of the chemical contaminants, because both may be defined in terms of source, transport, and receptor relationships. However, the sources, transmission, and measurement aspects of the physical contaminants are sufficiently different so that the problems associated with the analysis of the physical con-

taminants are not easily classified within the framework of analysis applicable to the chemical contaminants. Therefore, physical indoor air contaminants will also be excluded from consideration in this brief review.

Lifestyle and Dwelling Variables

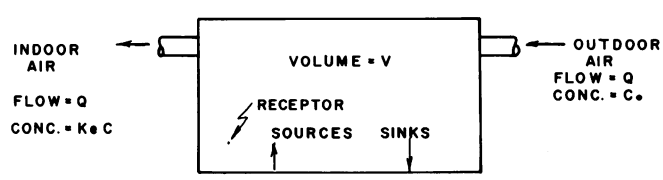
In an industrialized society, the majority of the population spends better than 90% of the time indoors. Even this estimate is subject to significant variations based on the chosen lifestyle of the subpopulations, climatologically determined constrictions, and, most importantly, the age and health status of the individuals. Those in poor health and very young children spend virtually all their lives indoors and as a further complicating factor, they live in certain restricted localities within the dwelling more so than do the healthy persons. Each of these observations has different implications in terms of the types and levels of exposure.

There are a number of studies that examine the time budget of the individuals to define the distribution of time spent in various activities (*2–4*). These studies indicate that employed men and women spend about 50 to 63% of their lives in their homes and homemakers spend about 82 to 90% of their lives in their homes. Unfortunately, these studies do not consider the age and health status of the population, although they give a good indication of the amount of time spent in private dwellings. As there are no specific data on this subject, it is reasonable to assume that neonates will spend at least as much time at home as homemakers, and the elderly will spend perhaps a little more. Furthermore, the infirm will spend almost 100% of their time at home. In addition to the amount of time spent at home, the fraction of time spent at home and spent in various subcompartments of the residential dwelling will also have an important effect on the types and levels of exposure. Although transfer of components between the rooms where the source(s) are located and the room where an individual might be found does occur, the estimates of the transfer parameters are generally not available. In addition, some of the significant sources of relatively unusual outdoor contaminants generated indoors through individual involvement with hobbies and crafts are self-selective in the degree of exposure. In other words, exposure to welding fumes far in excess of any occupational standard may be encountered in an amateur craftsman's basement. However, such exposure will probably be limited to the amateur welder and will probably present a lower challenge to the other inhabitants of the dwelling.

The level of contaminants in a dwelling is profoundly influenced by the exchange between indoor and outdoor air. Such an exchange defines the infiltration of the exterior contaminants into the dwelling and also controls the dissipation of the pollutants generated within the dwelling. The uniform measure of such an exchange is the ratio of the total volume of the dwelling to the air flow rate from the exterior of the building. Thus the normalized measure of flow is expressed in terms of air changes per hour (ACH). There are two components of the air exchange: (1) implemented ventilation and (2) infiltration. Although relatively common in commercial buildings and public facilities, specifically provided ventilation systems are rare in residential buildings. Therefore, in residential dwellings the air exchange is provided mainly by infiltration. The infiltration is significantly influenced by the type of construction, age of the house, and weather protection provided. In general, the air exchange rate in typical North American houses is between 0.5 and 1 ACH, with a typical value of 0.7 during the heating season. In newer houses constructed and prepared for savings in heating and air conditioning, the typical rates fall below 0.5 ACH and are expected to have a value between 0.2 and 0.5 ACH. Low income housing constructed between the turn of the century and the early 1970s will, in general, have higher air exchange rates than general housing, with about 20% exceeding 1.5 ACH (*5–7*). These air exchange rates are seasonal and strongly dependent upon micrometerorological influences and lifestyle. In pleasant weather it would not be unusual to find windows open in most dwellings. Furthermore, a considerable number of people prefer to have at least one window partially open even in the coldest weather.

Without specifically introduced air cleaning devices, the only significant removal mechanism for nonreactive gases is air exchange, whereas the reactive and nonconservative contaminants are removed by chemical reactions or transformations or by physical deposition in addition to removal by air exchange. It must be recognized that the inhabitants of a dwelling also do contribute to the removal of the contaminants simply by the process of inhalation and entrapment of the contaminants in the body. Although this process is very nearly insignificant as an air cleaning mechanism, it is, by itself, the definition of the exposure to the contaminant received by the individual.

There are a number of mathematical models based on mass balance performed on the box model of the con-



K_{ij} = Portion coefficient with source j and sink i at receptor

CONCENTRATION

RECEPTOR	INFLOW	GENERATION	REMOVAL	OUTFLOW

$$\frac{dC}{dt} = \frac{K_e Q C_o}{V} + \frac{\sum G_j}{V} - \frac{\sum K_{ij} R_i}{V} - \frac{K_e Q C}{V}$$

FIGURE 1. Parameters of a generalized model of ventilation.

taminated space which express the build-up and decline of contaminants as a function of time (*8–11*). The basis of these models is illustrated in Figure 1. Although these models use various degrees of sophistication, in general they represent the contaminant behavior only qualitatively. The generalized quantitative predictions hinge on a number of parameters which are normally either unavailable or virtually impossible to estimate unless the dynamics and the geometry of the system are artifically well controlled.

Similar to the air exchange between the outside and the inside of the entire dwelling, each compartment (room) within the building can also be represented by the same box model with the addition of any number of internal circulation loops. However, in this multicompartmental representation, infiltration will have to be modified with respect to the walls and openings exposed to outdoors and internal transfer rates equivalent to air circulation between the rooms which contain the sources and the target room. All other considerations with respect to removal, sources and mixing remain the same.

One of the most important parameters influencing the ventilation model is the mixing factor. Although heuristically it may be defined as deviation from ideal mixing or as virtual partitioning of the room air into fully mixed and nonmixed portions, its physical meaning resides in the spatial distribution of concentration. Therefore, the mixing factors may be expressed as a set of influence coefficients which relate sources and sinks to the concentration indicated at the receptor site. The first inherent complication in the estimation of mixing factors results from the complexity of the spatial distribution of air currents in a confined space. Even under well controlled circumstances, unless the scale of eddies is such that full mixing is achieved, nonuniform mixing will result. Nonuniform mixing necessitates the determination of local mixing factors. However, in general, for components which are not at immediately seriously toxic levels, such a refinement would not be necessary. An overall mixing factor would be a sufficient estimate for exposure prediction purposes. Even the estimation of overall mixing factors has inherent difficulties due to the variability of the mixing factor based on the geometry and the positioning of the air inlets and outlets with respect to the box under consideration. In a system where ventilation depends almost entirely on uncontrollable geometries (cracks, leaks, etc.), the estimation of the mixing factor becomes quite uncertain. To date, all direct measurements of mixing factors were made on systems where the experimental model is artificially ventilated. Even in these systems the mixing factor varies considerably (0.6 to 0.2). In general, in a system where the ventilation is dependent upon the natural supply of air through cracks and leaks, with little or no artificial circulation provided, the mixing factor can be as low as 0.02. It is important to note that the value of the mixing factor will determine the peak and average concentration at a given air exchange rate. If we use the simplest case of conservative contaminant with a constant generation rate as an example, the equilibrium concentrations for mixing factors of 0.02 and 0.6 will differ by a factor of 30.

The source emission rate is generally assumed to be a constant throughout the period of emission. This assumption is more due to the simplification it introduces to the equation than to the physical reality it may represent. In fact, in most cases the emission rates are back-calculated from an assumed model which may or may not have substantial agreement with reality. Therefore, generalizations from such estimates would be difficult at best. Fortunately, as in the case of local mixing factors, the precise knowledge of the source emission rates would not be necessary. An estimate accurate within a factor of 1.5–2 over the entire emission time would probably be of sufficient accuracy for a reasonable generalization. As important as the source terms, but usually harder to estimate, are the sink terms, which include the reaction rates for both chemical and physical removal mechanisms. The mathematical modeling and the measurement of these mechanisms are at best highly complicated and to date only a few estimates under specific conditions are reported (*13–17*). There are several reasons for the difficulties encountered in the estimation of the sink factors. For particulate matter, size-dependent deposition mechanisms require the knowledge of the size distribution of the aerosol, in addition to the geometry and the characteristics of the substrates (charged, uncharged, hot, etc.). In the case of gaseous reactive contaminants, the chemical composition of the substrates, the reaction rates with these substrates, as well as the system geometry, determine the controlling factors in the removal rates.

With very few exceptions, modern living takes place in designated areas of various activities such as cooking, eating, and entertainment. As these activities may represent different sources and as they take place in physically separated locations (subcompartments) of the overall box model, the compartmentalization will further complicate the resulting model. In addition to the general estimation problems mentioned above, internal circulation, the presence or absence of air cleaning devices, air distribution in the heating or cooling system, open doors, and location of air returns will all contribute to the determination of the air exchange between the compartments. These attendant difficulties are further aggravated by the lack of field data. Time spent in each subdivision, distribution of contaminants between subdivisions, the influence of a source in one room upon contamination at other rooms present important problems which hitherto remain relatively uninvestigated (*18*).

Indoor Contaminant Sources

The sources of indoor contaminants may be divided into three general categories which, in turn, may be further subdivided. The general categories are: (1) infiltrated contaminants, (2) contaminants generated by human activities, and (3) contaminants released from

Table 1. Categories of indoor contaminant sources.

Physical activity	Structure	Infiltration
Heating and cooking	Subsoil	
Habits	Water	
Pets	Furnishings	
House care		
Personal care		
Human activity	Building	

the structure itself or its furnishings. Table 1 represents this general classification and its subdivisions. The only major classification that has no subclassifications represents the infiltrated contaminants. In one sense this category is the easiest to represent since it can be backed by a myriad of data on outdoor air pollution; furthermore, there are a number of studies that present detailed accounts of the correlation between indoor and outdoor levels of pollutants which have outdoor sources (*18–20*). The data reported so far suggest that in all cases where there is no indoor source complementing the infiltration of the contaminant from outdoors, the indoor concentrations are lower than the corresponding outdoor ones. A reasonable estimate suggests a value between 1/4 to 3/4 reduction.

The indoor contaminants emitted from the parts of the structure, such as walls, floors, and ceilings, have been the most publicized indoor pollutants of recent years. In fact, two of these contaminants (asbestos and formaldehyde) have stirred sufficient public concern to receive national news media coverage. Shedding of asbestos from ceilings and high temperature insulation parts and emission of formaldehyde from particle board, plywood, and foam insulation may lead to exposure levels approaching those encountered in the industrial setting. Although the highest asbestos exposures encountered in nonoccupational environments are restricted mainly to public facilities, albeit rare, significant asbestos exposure may occur in private dwellings. In approximately 100 queries received and investigated by the University of Pittsburgh, Department of Industrial Environmental Health Sciences, we have encountered two such cases. In contrast, the formaldehyde concentrations which are at levels of immediate concern occur mostly in mobile homes and foam-insulated private dwellings. In severe cases, the exposure levels may exceed guidelines for industrial exposure levels (*21*). In addition to asbestos and formaldehyde, emission of solvents from newly painted areas, lead from chalking old paint, and fungicides included in latex paint may also be cause for some concern.

The parent nuclides of radon-222 are present in varying quantities in most of the common earth-derived building materials (e.g., cinder block, aggregate, building stone). The radon gas effusion from these products represents an important source for background radiation due to alpha-emitting radon daughters. A number of studies carried out in various parts of the country suggest levels about three times the outdoor concentrations (*18,22*). It is also reported that radon working level concentrations found in basements are about twice the levels found in upper floors or about six times the outdoor concentrations. The reason for this is the effusion of radon from the subsoil below the foundation. This source is significantly reduced by the type of construction (i.e., presence or absence of basements, slab construction or partial basements) and the geology of the region (*25,26*). Radon may also emanate from water, depending, of course, on the source of water supply (*18,22–24*).

The subsoil of a dwelling and tap water do not seem to be carriers of radon only. Houses constructed near or on hazardous waste disposal sites carry the possibility of having toxic organic matter sources in their basements. In addition, recent investigations carried out at the University of Pittsburgh suggest the effusion of organic contaminants from tap water (*28*). In a highly publicized case, airborne contagion has been traced to water as the initial carrier: the Legionella incident in Philadelphia captured significant attention and incurred a number of fatalities. The initial source of the infectious agent was in the cooling water of the air conditioning system. Since the incident, Legionella has been found in water systems in a number of locations, including private dwellings. Although the bacterial levels are low and although no incidence of disease resulting from contagion involving a private dwelling water system has been reported, such a possibility cannot be wholly discounted. The information on water as an indoor air pollution source, with the exception of radon, is only recently available and it is one of the areas which need further investigation.

Any human activity, even one as simple as walking across a room, is a potential source of generating contaminants. For example, the reentrainment of dust from carpets can result from such a simple activity. In addition to the reentrainment of settled dust from floors and carpets, furnishings present in a house may act as sources for contaminants: formaldehyde from green particle board or plywood, organic dust from deteriorating foam cushions, fibrous glass particles from curtains, or sand or other inorganic fillers from abraded carpets. Unfortunately, there has been no research in this area. The rates of generation and the types of contaminants generated depend upon a multitude of factors. Although obtaining such information would not be easy, nevertheless the data generated would be valuable.

The major combustion sources in residential dwellings are gas- and oil-fired furnaces and gas cooking appliances. The less important sources (in terms of usage) are kerosene-fired space heaters and wood- or coal-fired heaters. Properly operated heating sources which provide a flue for the combustion products contribute insignificant amounts to indoor pollution. However, unvented heaters and improperly operating furnaces do contribute significant amounts of nitrogen dioxide, sulfur dioxide, and carbon monoxide to the indoor environment (*29–31*). In homes which utilize gas appliances, kerosene heaters, or wood stoves, it is not unusual to

find levels of these contaminants 20 to 400% in excess of the outdoor concentration levels. In cooking with electric stoves and ovens, the only emissions are those contributed by the act of cooking, independent of the heat source. However, gas stoves and ovens, in addition to the emissions resulting from cooking, contribute significant emissions of carbon monoxide and nitrogen dioxide, especially in kitchen areas. The contribution of indoor combustion sources to indoor air pollution is one of the well studied aspects of the problem (*18,32,33*).

Smoking is not only one of the most significant sources of indoor air contamination, but is also the most thoroughly studied one (*18*). In general, approximately 90% of tobacco smoke is contributed in the form of gases, and the remaining 10% consists of some 2000 compounds which have been identified to date. Once emitted into the air, tobacco smoke mixes relatively rapidly with other constituents present. It is not known to what degree particles from cigarette smoke participate in chemical reactions while suspended in the air. Aging studies which have been performed on the disperse phase of tobacco smoke have been for periods of minutes after generation and not for periods up to 1 hr or more, a period of time relevant to exposure to environmental tobacco smoke.

Also, the chemical composition of tobacco smoke is altered by the variation of several parameters: burning temperature, type and blend of tobacco(s), substitutes and additives, cigarette length, paper porosity, and use of filters. In general, the mainstream (inhaled by the smoker) contaminant generation rates are higher than the sidestream contaminant generation rates. Although mainstream generation rate may exceed that of the sidestream for a given compound, the total weight of the compound produced in the mainstream may be much lower. Normally the mainstream is generated only about 20 sec per cigarette, resulting in a ratio of sidestream to mainstream generation time of 30:1. The differences in generation rates are primarily related to air flow and temperature differences during and between a puff. Puffing produces higher burning temperatures at the cone and consequently greater pyrolysis, but the hot airstream generated by puffing sweeps more gases and volatiles from the tobacco to the mainstream. Therefore, it is not surprising to find that the mainstream generation rates of CO, CO_2, and most volatile compounds exceed the sidestream rate.

Inhalation of mainstream smoke will result in selective reduction of constituent concentrations. Due to absorption and deposition, less than one-seventh of the original weight of volatiles and particulates is exhaled. Consequently, the sidestream must be considered the most important contributor to involuntary smoking.

Local mixing factors are expected to play a singularly important role in passive exposure to tobacco smoke. One may intuitively argue that a nonsmoker will seek to minimize exposure by choosing the most advantageous location with respect to the smoker(s) whenever possible, thereby reducing exposure to a level less than the one suggested by a generalized estimate. Conversely, under certain circumstances a nonsmoker may be at a highly disadvantageous location and be exposed to levels well beyond those suggested by a general estimate.

Since the outdoor concentration levels of total particulates for urban areas are approximately 50 to 300 $\mu g/m^3$ and for carbon monoxide approximately 1 to 5 $\mu g/m^3$, the level superimposed by smoking is, at least for a short duration, several times higher than these levels. In addition, all particulate matter generated by the smoking process is respirable, thus making tobacco smoke an important contributor to indoor air pollution.

House pets, with the exception of aquarium and terrarium dwelling animals, contribute dander to the indoor atmosphere. In addition, noncaged pets may act as sources in raising dust and providing lint through scratching furniture covers. Especially during moulting, pets may contribute significantly to indoor air pollution.

Probably the most important and least studied sources of chemical contaminants are house care products, personal care products, and hobbies. Almost all of these products are sold under trade names and either alone or in combination are capable of generating contaminants at levels immediately dangerous to health (*36*). The measurements of actual concentrations of contaminants produced by household and hobby products are few although those available indicate exposure can be far in excess of industrial exposure guidelines (*37,38*). In general, the few studies on consumer product exposures have been performed under laboratory conditions, and estimates for "worst reasonable conditions" suggest concentrations in the range of 50 mg/m^3 for respirable particles (*39,40*). It must be pointed out that deliberate or accidental inhalation of some sprays may lead to serious consequences or may even be fatal. Unfortunately, scant but perhaps highly thought-provoking results and even reported fatalities did not lead to any increased research activity in evaluation of exposure to contaminants of this type.

A large number of consumer products on the market bear the label "Use with adequate ventilation". It is reasonable to assume that these products, when used with care and adequate ventilation in industrial operations, would be sufficiently safe for healthy adults. Furthermore, the levels encountered will, in general, be less than the appropriate industrial exposure guidelines. But it must again be pointed out that the industrial exposure guidelines developed for these products—and often quoted in many legal cases involving serious health consequences of use—are essentially developed to provide reasonable safety for healthy adult workers. Therefore, they should not be considered as safe exposure guidelines for the population at large. With this in mind, it is not reasonable to assume that a person untrained in the control of intense sources would be able to gauge what adequate ventilation might be for general use. In fact, even for a trained person to determine adequate ventilation for each of the plethora of products available would be a huge task, especially when the components

of the products are not generally printed on the label or printed under trade names. A further complication may arise from good intentions. An improperly placed fan may create more problems than it would solve and thus may result in higher exposures. As it was pointed out, extensive exposure to some of these contaminants may indeed have disastrous health effects. An excellent example of this is the availability of two-component polyurethane lacquer sold in professional paint stores for high quality finish in repainting cars and furniture. The health effects of exposure to isocyanates—sensitization and resultant chemical asthma—are well discussed in the industrial hygiene literature. Although these product may be clearly labeled to indicate that the product is designed to be used by professionals, normally the label does not indicate whether the results obtained by the amateur user of the product would be less than satisfactory or that such a designation carries health considerations.

This type of argument may also be carried to house cleaning products of many different kinds. For example, ammonia mixed with chlorine-based bleaches will emit ammonium chloride, an irritant which, if inhaled, may result in a serious lung disorder. Neither ammonia nor chlorine-based bleach bottles have such a warning. Another example is inadvertant use of welding or soldering flames on PVC, which will result in deadly combustion byproducts (mainly hydrochloric acid fumes). Therefore, any significant research on any one of the aspects (prevention, effects, etc.) of this subject carry some urgency. However, no current effort of any significance is known to this author.

Household pesticides, fungicides, and other pest control products represent an interesting class on their own. A large number of insecticides come with spray devices which are designed to produce aerosols. As yet, no report is available on the inhalation potential introduced by the household use of such pesticides. Although many of these products contain a warning stating that the product is harmful if swallowed or inhaled, it is not known how inhalation can possibly be prevented if the products are used indoors.

Summary and Conclusions

This brief overview of the status of indoor air contaminants suggests that although a considerable body of knowledge exists on a number of contaminants such as nitrogen dioxide, formaldehyde, tobacco smoke, sulfur dioxide, and radon, all of which can have serious health consequences, there are very large gaps in knowledge on sources and types of contaminants with possible health consequences. It is both reasonable and appropriate to expect that hitherto so-called priority pollutants of the outdoor environment be more intensively studied to discover their indoor pollution potential. However, it must also be remembered that these contaminants have been classified as priority pollutants because of the existence of significant emission sources which influence the outdoor environment. Therefore, they may not necessarily be the priority pollutants for indoor environments. The lack of research on exposure to consumer products and possible health effects of hobby and craft products leave a major gap in research on health effects of indoor air pollution. The difficulties associated with such research are the challenges for future research on this topic.

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