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BUILDINGS OF THE 21ST CENTURY: A PERSPECTIVE ON HEALTH AND COMFORT, AND WORK PRODUCTIVITY

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ABSTRACT

Humans have been constructing buildings for over 10,000 years. Over the centuries, buildings have grown in both size and complexity. As we have made transitions from agrarian to industrial and post-industrial eras, we have come to spend more of our time in indoor environments. In developed countries, people typically spend more than 90 % of their time indoors. Thus, buildings dominate our lives.

We have long understood that building environments can have substantial effects on health, comfort and behavior. This understanding has been translated into building designs and operations with the objective of providing healthy, comfortable, livable and productive conditions. With the construction of increasingly more complex buildings, there is a need for a more sophisticated understanding of how buildings affect our health and comfort and the relationships between health and comfort. Our current efforts to understand these effects, however, generally focus on pairwise relationships, e.g., the effect of ventilation or temperature on comfort. Furthermore, we are hampered by the lack of objective measures of the dependent variables of concern. For example, we use self-reporting of comfort and symptoms of illness.

By the year 2025, we will need to have a much more integrated and quantitative understanding of the multifactorial relationships between dependent variables related to health and comfort and the environmental factors that control these variables. We will also need more objective measures of the health and comfort endpoints, e.g., brain wave patterns, concentrations of endorphins, pollutants, etc., in body fluids. Advances in molecular biology, neurology and toxicology have great potential for providing such measures. These will enable us to develop relationships of the form:

$$E = f(V, T, H, P_i, L_i, ...J, O, B, S,....),$$

where E is some measure of health, comfort or productivity, V is ventilation, T is temperature, H is humidity, P_i are the concentrations of pollutants in indoor air, L_i is light intensity, at various wavelength, J is a measure of job satisfaction, O is a measure of organizational factors, B is job benefits, S is job-related stress. Matrices of such equations could then be used in both the design and operation of buildings to maximize human health and comfort.

We are already seeing the beginning of efforts to design "smart buildings" controlled by microprocessors which are linked to various sensors in the buildings. Sensors will be developed for other variables which affect our comfort, health and productivity. By the 2025, many residential and commercial buildings will be computer controlled to maintain optimal indoor environments for livability and work productivity. User friendly software combined with the use of sensors located within microenvironments and new environmental control equipment will provide greater flexibility and individual control of microenvironments.

INTRODUCTION

Humans have been constructing buildings for over 10,000 years. The first buildings were probably constructed to provide thermal control and shelter from the elements. This had beneficial effects on both comfort and health. It is likely that there were also some adverse health effects such as exposure to combustion products from fires. As civilization has progressed, humans have become more dependent upon buildings and buildings have become increasingly complex. Humans in the developed countries have come to spend an average of about 90 % of their time in buildings (Szlai, 1972; Chapin, 1974). As shown in Figure 1, even in the developing countries, urban dwellers spend about 88 % of their time indoors, while rural populations spend about 60 % of their time indoors (Smith, 1988). *Thus, buildings have come to dominate our lives!*

The purpose of this paper is to examine our understanding of the relationships between the dependent variables of health, comfort and productivity and the environmental and other factors (independent variables) which influence these in the context of buildings and building practices. Trends that are likely to have impacts on buildings of the 21st Century are discussed.

TRENDS THAT WILL HAVE IMPACTS ON BUILDINGS

As we move into the 21st century, the trend toward construction of more complex buildings is likely to continue. There are certain trends that are likely to have substantial impacts on the design, construction and operation of buildings and on the health, comfort, and productivity of building occupants.

Climate and Air Pollution

Global warming, due to increased atmospheric concentrations of greenhouse gases, has been predicted. There is already evidence of a global temperature increase of 0.5^{O}C over the past century (Hileman, 1989), although the cause of this increase is not yet clear. If present emission trends continue, a 3.5^{O} to 4.5^{O}C global warming is predicted over the next century (Hileman, 1989). The models indicate that warming will be greater at the high latitudes than in the tropics and that heat waves will occur more frequently. Significant changes in rainfall patterns are also anticipated. Global warming in combination with greater expectations for comfortable homes and work environments, is likely to increase the demand for cooling in buildings to maintain comfort and productivity. Energy usage for winter heating may decline. Since much of the energy used for heating and cooling buildings comes from fossil fuel combustion, which emits greenhouse gases, there is likely to be a greater demand for energy conservation to bridge the transition to renewable and less environmentally polluting energy sources. This will mean more energy-efficient and tighter buildings, with lower air exchange rates, and more energy efficient lighting and appliances.

More outdoor air pollution seems likely in the future, despite efforts to reduce emissions from motor vehicles, space heating, power production and industrial sources. Increased populations in some developed countries and in most lesser developed countries will mean greater air pollution. In the U.S. reductions in mass of emissions per unit motor vehicle have not been sufficient to offset the increased number of vehicles on the road. Population increases also lead to the need for more homes (with heating and cooling demands), jobs and consumer products and consequent increases in pollution.

Increased temperatures, particularly in urban areas, may exacerbate photochemical smog during summertime. Wilson (Rosenfeld, 1989) has analyzed data from Los Angeles and found a trend toward increased numbers of days when the ozone concentrations exceeded the standard as urban temperatures increased (Figure 2). Use of alternative fuels (e.g.,woodburning) for winter space heating in the U.S. has increased both outdoor (Cannon, 1984) and indoor (Sexton et al., 1986; Daisey et al., In Press) air pollution in certain parts of the United States. Such trends are likely to increase the demand for air cleaning, particularly during certain times of the year. For example, removal of ozone from outdoor air used to ventilate buildings such as hospitals and schools might be needed during air pollution episodes to protect the health of more vulnerable populations.

Population and Lifestyle Changes

There have been very significant changes in lifestyles as the developed countries went from agricultural to industrial to post-industrial economies and populations grew. In these countries, mastery over many infectious diseases, clean water supplies, education, etc., have led to a greater average life expectancy. In the U.S., by the year 2000, persons over 65 are expected to represent 13% of the population; by 2030, they are expected to constitute 21% of the U.S. population. This may mean an increase in the age of retirement, i.e., more senior citizens working full or part time beyond the age of 65. The consequences for buildings are likely to be greater demands for safety and comfort features such as automatic stove shutoffs, support bars in bathrooms, better lighting (since visual acuity decreases with age), easier cleaning, more zone control of temperature, and "smart houses."

Birth control has probably had one of the greatest impacts on how we live in the late 21st century in the developed countries. This has led to smaller family sizes, more women in the workforce, and greater economic independence for women. Greater life expectancy and more control over family size have led to more diversity in the meaning of the word family. In the industrial age, family came to mean the "nuclear family," i.e., working father, mother at home and children. In the post-industrial age, we have come to see many more single parent families, combined families of parents and children from previous marriages, unmarried couples (of every age) and various combinations of related and unrelated people sharing the same household. This has led to a diversification in housing needs and movement from one house type to another during different stages of life. With more women working outside of the home and many more single-person households, demands for "smart houses" and more easily cleaned and maintained houses will increase. New materials and design as well as development of robot cleaners have the potential to meet this need. A more diverse workforce which includes more elderly people, pregnant women, handicapped people, etc., will also result in a demand for safer, more convenient and more healthful buildings.

The Information and Communications Society

Innovation in communications and computer technologies over the past few decades have led us from the industrial age to the post-industrial age. Naisbitt (1982) has termed the post-industrial age the information age. He has pointed out that more than 65% of the U.S. population works with information in one form or another, e.g., programmers, clerks, accountants, secretaries, teachers, managers, stockbrokers, insurance people, bankers, scientists, etc. Computers and electronic communications now permeate the workplace, even in the industrial sector. Computers have provided the means for us to automate, speed-up, and control processes, machines, equipment, business operations, and many other aspects of modern life. Computers and communications networks have also provided the means for people to work at home. Few people have chosen to work at home 100% of the time, probably because we are a social species and the workplace provides some social interactions, both personal and work-related. However, some people are choosing to work at home with computers several times a weeks or for certain periods, e.g., mothers or fathers of young children. In the future, we should see more such flexibility in working locations and hours because of the advances in computer and communications technologies. Traffic congestion in many U.S. urban areas may accelerate such trends.

Computer and communications technologies are already beginning to be designed into homes. The National Research Center of the National Association of Home Builders in the United States is spearheading a program to develop a "Smart House" (Smart House Development Venture, 1987). The "Smart House" will use a single-cable wiring system for energy distribution, for communication and for functional control of the house. The intended benefits of the system include substantial reduction of shock and fire hazards, simplified electromechanical appliances, expanded communications, automation, home security and personal health applications, less costly metering of natural gas, electric power and water, a backup system in event of power failure and the potential for improving functionality without wiring system constraint. Mitsubishi Electric Sales America, Inc., is now marketing a home automation system to control home energy consumption by controlling various appliances, home security, house communications and home entertainment centers.

In office environments, systems are already being developed to provide personal control over individual work environments. The Tate "Task Air"® system, for example, is designed around a modular access floor in which the space beneath the floor serves as a supply-air plenum and allows easy installation of wiring (e.g., telephone and computer cables). Air is supplied from the sub-floor plenum to the office space through "Task Air®" modules. Each module is interchangeable with individual access panels providing a high degree of flexibility in the number and locations of air supply outlets. Task Air modules located near work stations can be manually adjusted by workers to control the flow rate and direction of air to meet their individual needs. "Personal Environments®", a similar system, developed in prototype by Johnson Controls, Inc., also involves distribution of air and utilities to individual offices through a raised floor. In addition, each work space has individual controls for temperature and lighting and an air cleaning system. "White noise" can be generated by the individual to cover background noise from neighbors.

Advances in Biological Sciences

Advances in the biological sciences are likely to have some of the greatest impacts on how we live in the 21st century. We are beginning to see progress in efforts to diagnose and treat chronic diseases such as heart disease and cancer. Advances in molecular biology, exposure assessment and epidemiology will provide an understanding of the causes of chronic disease and lead us to be able to prevent rather than treat such diseases. Gene-transfer technology will enable us to prevent and cure genetic diseases and disabilities. Transplants of organs from donors are already common in the U.S. As our understanding of cellular processes and organ development and function grow, we may be able to grow new organs in the laboratory to replace diseased or aged organs. We are making substantial progress in our efforts to understand how the human brain works at the chemical and electrical level and at the systems level. Knowledge about brain function could lead to a variety of applications including direct control of equipment through the brain, ability to monitor productivity in workers for research, etc. Investigators at Stanford University, for example, are working on an electronic system for controlling musical synthesizers with bioelectric signals from muscles, brains and eyes (Amato, 1989).

We are also learning to measure many biologically important molecules that may be useful indicators of biological state (endorphins, melatonin, etc.), of exposure to toxic chemicals (metabolites of the toxic compound, DNA adducts,etc.), markers of adverse effects of toxic chemicals and radiation and early indicators of disease (activation of oncogenes). Such advances in the biological sciences will provide many of the tools needed to determine relationships between building environmental factors and human health, comfort and productivity.

It is safe to predict that genetic engineering and biotechnology will not be used to produce people to fit the buildings of the future! However, advances in the biological sciences in general should lead to longer-lived populations.

THE DEPENDENT VARIABLES: HEALTH, COMFORT AND PRODUCTIVITY IN BUILDINGS

The health and comfort of building occupants are important objectives to consider in designing, constructing and operating buildings. In office buildings, for example, it is estimated that more than 90% of the cost of operating a building over its 45 year lifetime is employee compensation. Thus, the health as well as the comfort of the building occupants is increasingly being recognized as important objectives for building design and operation. Both health and comfort may be considered dependent variables for which we wish to know the determinants or independent controlling variables and the functional relationships:

$$\text{Health} = f(x_1, x_2, x_3, ...x_i),$$

$$\text{Comfort} = f(y_1, y_2, y_3,.....y_i),$$

where x_1, x_2, ...x_i, and y_1, y_2, y_3, ...y_i are the independent variables which determine health and comfort, respectively.

The Constitution of the World Health Organization defines health as a "state of complete physical, mental and social well-being and not merely the absence of disease" (WHO, 1988). Comfort is implicitly part of this definition of health. Comfort, according to the definition adopted by ASHRAE (1981), is "the state of mind that expresses satisfaction with the environment." Comfort is generally measured by asking subjects to rate their satisfaction with a specific environmental factor over a range of settings with other variables held constant. For building design and operation, relationships between comfort and the environmental factor of interest are commonly expressed as the percentage of people satisfied at a given setting of that variable, e.g., temperature. Direct measurement of human response works reasonably well in a controlled laboratory setting. It is more difficult to measure comfort in a real-world setting through the use of direct questions or questionnaires because the act of questioning can itself bias the subject. Furthermore, it is necessary to obtain permission for such real-world experiments. There are also differences between a real building and a controlled environmental chamber which can affect the measured variables. For example, based on the ISO7730 limit for mean air velocities, less than 5 % of the occupants are expected to be thermally dissatisfied. Fanger and co-workers (1988) have found that in typical environments, 15 to 20% are dissatisfied even if ISO7730 is observed due to differences in air movements in rooms compared to environmental chambers. Thus, development of instrumentation to measure thermal comfort parameters in real buildings can be very useful. Madsen et al. (1988) and Mayer et al. (1988) have recently reported work on the development of meters to measure local thermal comfort caused by draft and/or radiant heat loss. The idea of these meters is to simulate the human sensation of local heat loss from skin.

Our current concerns regarding health in buildings are about a variety of different adverse health effects, long and short-term, acute and chronic. Many of these are listed in Table 1. The adverse health effects currently of concern range from very serious, life-threatening and life-shortening diseases such as cancer and asbestosis, to lesser health effects such as headaches. In some instances, a single agent is associated with the health effect of concern, e.g., CO poisoning, asbestosis. More frequently, a variety of chemical and physical agents in the indoor environment can contribute to or cause a given adverse health effect. Linking adverse health effects to causative agents in the indoor environment is a difficult process even when there is strong evidence that the building itself is somehow causing the effect. In order to link cause and effect, the variables of interest must be measureable. For many of the health endpoints of concern, we do not have very good or objective measures. For example, headaches, nausea, inability to concentrate, are generally self-reported. More specific and objective indicators of the many health effects of interest are needed to support our efforts to link cause and effect.

Productivity is also a dependent variable but one which differs somewhat from health and comfort. The latter two variables refer to states of a subject while productivity refers to the output of a worker. Furthermore, productivity is generally assumed (and there is some evidence to support this) to be dependent, at least in part, on good health and on the comfort of the worker. Productivity denotes the quantity, quality and timeliness of an individuals work performance (Stokels et al., 1988). Productivity can be measured reasonably well for many industrial jobs, e.g., number of person-hours to produce a car. Certain types of routine office work and service work are also amenable to productivity measurement. For many workers in the information and communications society, however, productivity is difficult to measure because of the nature, diversity and complexity of the work and the product. The products are the generation, organization, integration, evaluation and communication of information. Since the fraction of the workforce involved in information activities is increasing in the developed countries, there is a need to develop new and better methods for measurement of worker productivity in such jobs.

THE INDEPENDENT VARIABLES CONTROLLING HEALTH, COMFORT AND PRODUCTIVITY

In order to design, construct and operate healthy and comfortable buildings for the 21st century, it is necessary to understand the independent variables that determine health, comfort and productivity in building occupants in a quantitative way. Furthermore, the environmental factor(s) which are measured must be the causative ones and must be measured at the right time and place with respect to the effect of concern. For health effects that occur only after many years of exposure, improved methods for estimating exposures to the agents of interest over that time period are needed.

Comfort

The factors controlling indoor comfort tend to be physical, e.g., temperature, humidity, ventilation, air velocity, odor, lighting, noise, etc. Indoor air quality and physiological and psychosocial factors, however, can also affect our comfort. We now have some quantitative understanding of many of the relationships between thermal comfort and the independent physical variables controlling thermal comfort in buildings. Development of this level of understanding has been based upon applications of the fundamental principles of thermodynamics and human physiology combined with experimental work in laboratories and some work in buildings. Fanger's comfort equation, for example, is based on a rationally derived heat balance equation for the passive state during thermal equilibrium and experimental observations (Fanger, 1972). This has led to Generalized Comfort Charts (ASHRAE, 1981) which take into account air temperature, mean radiant temperature, water content of air, relative air velocity, clothing and activity level. The independent variables that are required can be readily measured and/or controlled in the laboratory. More measurements are now being done in the field (in real-world settings). Schiller and co-workers (1988), for example, have developed a mobile measuring system for field measurements of air velocity, air temperature, radiant temperature, air velocity, humidity and illumination. Sensors are located at ankle, mid-level and head/neck levels. The mobile measuring system is moved to each work station. Subjective measurements of thermal comfort were also made in order to compare the subjects responses to the measured thermal environments. Similar, although perhaps not so advanced, approaches are being used to develop quantitative relationships between comfort and other variables such as odor, lighting, noise and ergonomics, i.e., application of fundamental principles of physics, chemistry and biology to the problem in combination with laboratory and field experiments.

Health and Indoor Air Pollution

The independent variables which control health are more complex, in many respects, than those which control comfort. They include air quality, lighting, ergonomics, psychosocial factors, etc. Each of these independent variables is quite complex and often it is difficult to clearly relate cause and effect. Indoor air quality, for example, is determined by the concentrations of multiple pollutants from multiple sources. As discussed above, different pollutants can have different health effects. Furthermore, some pollutants may act in combination with other pollutants or other variables to cause an adverse health effect.

Over the past decade, it has become clear that environmental health risks from airborne pollutants can be much greater from indoor than outdoor exposures. Two factors account for the greater risks: 1) people spend 70 - 90 % of their time indoors (Szlai, 1972; Chapin, 1974); 2) concentrations of many airborne pollutants are higher - sometimes by one or two orders of magnitude - in buildings than in outdoor air. Energy conservation measures resulting in lower ventilation rates for buildings can exacerbate indoor air quality problems, particularly if the pollutant is from indoor sources. New materials used in buildings for energy conservation or other purposes can also be sources of indoor pollutants, e.g., urea formaldehyde foam insulation.

Major indoor pollutants currently of concern include radon, combustion source emissions, volatile organic compounds (VOCs), including formaldehyde, and biological agents. Radon, a chemically inert gas, can enter building substructures by pressure-driven flow of soil gas; this convective flow is driven by the pressure differential between the building and the surrounding soil induced primarily by temperature differences between indoor and outdoor air and wind loading on the building superstructure (Nazaroff et al., 1985; 1987). Thus, the building itself is a strong determinant of indoor radon concentrations and the consequent health risk. Emissions from combustion sources such as cigarettes, gas stoves, and unvented space heaters, include pollutants such as CO, NO_2, VOCs and particulate matter. For typical residential ventilation rates, pollutants from indoor combustion sources can build up to fairly high levels, in some instances, levels that present some risk of an adverse health effect. The VOCs include compounds such as benzene, toluene, methylene chloride, etc. Many of the VOC are solvents and as such are widely used for fabricating materials and consumer products found in indoor environments. Like radon, VOC also can enter buildings by pressure-driven flow of soil gases contaminated by nearby landfills or hazardous waste sites (Hodgson et al., 1988) and can be released into indoor air from usage of contaminated water (McCone, 1987). Outdoor air, through infiltration or ventilation, can contribute to or dilute indoor levels of pollutants. Samet et al. (1987, 1988) have recently reviewed the various health effects associated with many of these indoor pollutants and discussed the evidence for the health effect of concern for various agents at indoor levels.

Nero (1988) has pointed out that the long-term health risks posed by indoor air pollutants are, in fact, comparable in magnitude to those associated with exposures to chemicals or radiation in industrial settings. Figure 3, from Nero (1988), compares the estimated lifetime risk of premature death from lifetime exposures to various indoor air pollutants to the risks from automobile and home accidents, certain jobs, cigarette smoking and outdoor exposures to certain air pollutants. The estimated probability of suffering a fatal disease is substantially higher for exposures to indoor air pollutants than to pollutants in outdoor air and drinking water. Risks of cancer due radon are about 0.3 % for lifetime exposure at the median indoor concentration measured in single family homes in the United States, 1.5 pCi/l (56 Bq/m^3). Nero (1986) has estimated that approximately a million single family homes in the U.S. may have radon concentrations exceeding 8 pCi/L implying an individual lifetime risk greater than approximately 2% to lifetime occupants.

Many of the VOCs found in indoor environments, e.g., benzene, formaldehyde, are carcinogens. Work by McCann et al. (1986) suggests that lifetime indoor exposures to VOC may pose a risk of cancer only slightly lower than that due to radon. Similarly, indoor exposures to environmental tobacco smoke (ETS), smoke to which non-smokers are exposed from being in a building with smokers, poses some risk of lung cancer (NRC, 1986; Samet et al., 1987). Exposures of children to ETS can also contribute to increased respiratory illness, with concomitant absences from school. It should be noted, however, that our estimates of cancer risks from indoor exposures to pollutants such as ETS and VOC have much greater uncertainties than risk estimates for radon exposures. For the ETS and VOCs, there are greater uncertainties in estimates of both the exposures and the risk coefficients, i.e., the risk of an adverse health effect per unit exposure. Risk estimates for long-term health effects, i.e., those health effects that are observed only after a long period of exposure or late in life (e.g., cancer), are generally based on poor exposure estimates and extrapolation of animal dose-response data to humans. The animal experiments are conducted at high exposure levels and are typically for a single agent while humans are exposed to many environmental agents, each typically at a low level. The costs of many of these illnesses, however, can be very high in terms of medical costs, lost productivity and human suffering. Thus, there is a need to better understand the causes and effects of indoor environmental agents in a quantitative way so that cost-effective strategies can be developed to reduce any substantial risks.

"Sick building syndrome" (SBS) and building related illness (BRI) are receiving increased attention because of their easily observed effects on worker health and productivity. BRI has been defined as sub-chronic disease or symptoms caused by one or a few environmental parameters near a threshold concentration above which health effects are expected. SBS, on the other hand, involves occurrence of sub-chronic symptoms in workers in buildings in which no single environmental parameter is near a health threshold. Thus, the cause(s) of SBS are not currently understood. Inadequate supply of outside air, VOC released from materials in the building, inadequate control of temperature and humidity as well as artificial lighting, static electricity, lack of privacy and psychological factors have all been suggested to play a role. Interactions among certain of these factors may be as or more important than the individual factors.

We have estimated that BRI and SBS cost the U.S. about 160 million dollars annually in lost productivity, building diagnoses and environmental measurements. This estimate does not include costs for mitigation or litigation. Clearly, there is a need to understand the causes of both BRI and SBS so that buildings can be constructed and operated in such a way that workers remain healthy and productive.

Biological agents in indoor air can cause infectious diseases and allergic reactions. These agents include viruses, bacteria, fungal spores, algae, amoebae, arthropod fragments and droppings and animal and human dander (Burge, 1983). Many of the biological agents which cause adverse health effects require moisture and nutrients in order to proliferate to a point at which they cause illness. Humidifiers, air conditioning systems and water-damaged areas or materials in a building can provide suitable environments for proliferation of microorganisms. Many of the materials in indoor environments can supply the needed nutrients (chiefly carbon) as well as moisture. Cellulose- or lignin-based materials, for example, when damp, can provide ideal enrichment media for the growth for a wide variety of bacteria and fungi (Burge, 1985). Aerosolization and distribution of microbial agents from HVAC system components such as humidifiers, air washers, etc., is fairly common. Thus, the materials selected for building construction as well as the building design and operation can strongly influence airborne concentrations of biological agents which cause adverse health effects.

The growing recognition of the significance of indoor air pollution is already beginning to affect building technology. In certain areas of the U.S. with high indoor radon levels, builders are beginning to construct homes with radon control systems and many homeowners are retrofitting their homes with radon control systems. Devices for continuously monitoring radon are being marketed. Requests for information on building materials with low VOC emissions are increasing. This trend can certainly be expected to grow and to be extended to other indoor pollutants as well. The use of monitoring devices requires knowledge of healthy and unhealthy levels for the pollutant of concern. For some indoor air pollutants, relationships between the adverse health effect and the concentration of the pollutant are sufficiently well understood that standards already exist for outdoor air and industrial workplaces, e.g., CO_2, CO, NO_2, particulate matter, asbestos. Guidelines for indoor air quality in residences and non-industrial workplaces are being developed for many indoor pollutants (Health and Welfare, Canada, 1987), frequently based on outdoor and industrial standards. There are some problems in adapting industrial standards to residential, commercial, and public buildings. Industrial exposure standards are typically for situations involving exposures to one or a few pollutants at high levels. Furthermore, the exposed population is the healthy worker. Exposures in non-industrial settings typically involve much lower levels of pollutants but exposures to many different pollutants (the sum of which is often equivalent to concentration levels for individual industrial pollutants). In addition, more vulnerable populations are exposed, e.g., children, pregnant women, chronically ill persons, elderly, etc. For such situations, more work will be needed to insure that reasonable standards are set.

In the developing countries as well as the developed countries, indoor air pollution also tends to be greater than that outdoors. Because of the greater usage of unvented cookstoves in many developing countries and the types of fuels used (e.g., wood, dung, straw, coal), indoor air pollution and human exposures to many pollutants tend to be considerably greater in buildings in developing countries than in the developed countries (Figure 4, Smith, 1989). Hopefully, we will see a trend in the developing countries toward greater use of exhaust ventilation and more energy efficient cook stoves with lower pollution emissions in the 21st century.

Health and Lighting

Most indoor lighting is artificial. Approximately 80% of indoor lighting is supplied by incandescent lamps while 20% is supplied by fluorescent lamps (Thorington, 1985). Both the intensity and spectral distribution of indoor lighting differ substantially from natural sunlight. Table 2 presents a comparison of natural sunlight and cool, white fluorescent lamp lighting which is used commonly in offices and other work places. For general office lighting, the recommended practice is currently about 200 to 1000 lux. These levels correspond to illuminance levels associated with twilight in the outdoor environment. The levels (and percentages) of UVA and UVB differ substantially from sunlight. In addition, there is usually a near subliminal flicker associated with these lamps. Light levels too low for the task at hand and/or glare can cause discomfort at the very least.

Berman et al. (1987) have found significant differences in pupil size occur when subjects are exposed to high-pressure sodium lamps as compared with indirect incandescent lighting with photopically match light levels. They suggested that the difference in pupil size was most likely due to differences in the spectral power distribution of the two lighting systems. Since pupil size affects visual performance, there could be adverse effects on worker productivity and possibly eyestrain from use of lamps with certain spectral distributions. There has been a recent report of headaches associated with exposures to lights with a certain flicker frequency. Wilkins et al. (1988) have reported that headaches and eyestrain in office workers were reduced by half or more when lighting circuitry was altered so that the light did not fluctuate in intensity.

Melatonin levels in humans may also be adversely influenced by indoor lighting. Melatonin is a hormone secreted at night by the pineal gland. Nocturnal release in humans and other species is rapidly suppressed by exposure to sufficiently bright light. Melatonin at pharmacological levels has been shown to have brief, but substantial, sedative effects on mood and performance in a laboratory setting (Lieberman et al., 1985). Reiter (1985) has shown in animal experiments that the duration, irradiance and wavelengths of light all can impact the pineal gland through the retina of the eye to influence melatonin levels. For humans, the level of illumination sufficient to suppress nocturnal secretion of melatonin is about 5 to 10 times greater than typical artificial indoor illumination levels.

Indoor lighting levels and the amount of UVB (290 to 315 nm) in indoor lighting may not be adequate to maintain vitamin D levels and calcium balances in humans who spend most of their time in buildings. Davies (1985) deprived young men of light <380 nm for 10 weeks but fed them a normal (British) diet, which each subject selected. Depletion of vitamin D stores sufficient to cause inadequate intestinal absorption of calcium was observed, with increasingly negative calcium balances after 6 weeks.

There are probably other as yet undiscovered health effects of indoor lighting. Wurtman (1985) has noted that many compounds in tissue and blood absorb visible and ultraviolet light *in vitro* and are altered. He has speculated that particular spectral bands will be found to affect blood or tissue levels of many biologically important molecules not currently perceived as light-dependent.

Productivity

Traditional theories of productivity have been based on the assumption that employee satisfaction is a strong determinant of productivity (Wineman, 1986). The assumption has been that if employee satisfaction is high, motivation is high and there is a resultant high level of performance and productivity. There is evidence to support this assumption but the relationship is not as strong as had been assumed (Lawler and Porter, 1967). Lawler and Porter (1967) proposed that rewards, extrinsic (those controlled by the organization, such as pay and status) and intrinsic (feeling of accomplishment) are stronger determinants of worker productivity than employee satisfaction.

Health and comfort (and the variables which determine these) are also independent variables which influence worker productivity. In recent years, there has been more interest in the environmental conditions of buildings which influence worker productivity (e.g., Stokols et al., 1988). The quantitative relationships between worker productivity and environmental variables, however, are not yet well developed. Illness and discomfort can clearly have adverse effects on worker productivity. For example, if a worker is absent due to a cold, production is zero. If workers are experiencing "sick building syndrome", there is generally a reduction in productivity, although this is not well quantitated. However, the functional relationships between productivity and health, comfort and their determinant variables is probably not linear. The functionality may be more of a step function. That is, there may be a linear relationship between productivity and health for significant illness but at some level the slope of the relationship becomes flatter. Thus, a given increment in health or comfort state may not yield a large increment in productivity beyond some point.

RESEARCH NEEDS FOR HEALTH, COMFORT AND PRODUCTIVITY IN BUILDINGS OF THE 21ST CENTURY

As we move into the 21st Century, it is highly probable that the trend toward increasingly complex buildings will continue and even accelerate. New materials and new systems will be introduced into buildings, generally without adequate evaluation of their potential impacts on human health and comfort. With such buildings, we will be dealing with interactions between two complex systems - one biological (humans) and one mechanical (buildings). Humans design, construct, operate and function within buildings. Buildings, in turn, have impacts on our health, our comfort, our psychological states and our culture. We need to use the knowledge we already have more effectively. We will also need to learn much more about certain aspects of the interactions of buildings with people in order to have "healthy" and comfortable buildings. Specific research needs include:

1. Better tools and methods for measuring adverse health effects, comfort and productivity; more objective measures of the health and comfort endpoints, e.g., brain wave patterns, concentrations of endorphins, pollutants, etc., in body fluids. Advances in molecular biology, neurology and toxicology have great potential for providing such measures.

2. Improved methods for measuring exposures to environmental factors affecting health, comfort and productivity;

3. Improved methods for assessing risks of adverse health effects;

4. More integrated and quantitative understanding of the multifactorial relationships between dependent variables related to health and comfort and the environmental factors that control these variables to enable us to develop relationships of the form:

   $$E = f(V, T, H, P_i, L_i, ...J, O, B, S, ...),$$

   where E is some measure of health, comfort or productivity, V is ventilation, T is temperature, H is humidity, P_i are the concentrations of pollutants in indoor air, L_i is light intensity at various wavelengths, J is a measure of job satisfaction, O is a measure of organizational factors, B is job benefits, S is job-related stress. There is a need to determine the functional relationships between these variables and to determine which variables have the greatest influences on the dependent variable of interest. Matrices of such equations could then be used in both the design and operation of buildings to maximize human health and comfort.

5. User friendly software combined with the use of sensors located within microenvironments and new environmental control equipment to provide greater

flexibility and individual control of microenvironments;

6. Systematic approaches to evaluating potential adverse health and comfort effects of new buildings materials and systems *before* they are widely incorporated into buildings.

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TABLE 1. SOME ADVERSE HEALTH EFFECTS ASSOCIATED WITH ENVIRONMENTAL AGENTS OR FACTORS IN BUILDINGS

Cancer	Dermatitis
Asbestosis	Immunological effects
Cardiovascular disease	Allergies
CO poisoning	Changes in pulmonary function
Asthma	Headaches
Upper respiratory infections	Nausea
Legionnaire's disease	Depletion of Vitamin D
Pontiac fever	Effects on other hormones?
Eye and respiratory tract irritation	Effects on melatonin

Table 2. A Comparison of Natural Global Radiation and Artificial Radiation from Cool White Fluorescent Lamps with Diffusers[a]

Property	Natural Global Radiation[b]	Cool White Fluorescent Lamps (UVB absorbing)
Illuminance (lux)	113,285	50 ------>2,000
Percent flicker	0	16-34%
290-830nm Irradiance (Wm^{-2})	611	0.16-6.4
UVB (290-315 nm): Irradiance (Wm^{-2})	1.54	0
Percent of Total Irradiance	0.25%	0%
UVA (315-400nm): Irradiance (Wm^{-2})	57.7	<0.006-0.24
Percent of Total Irradiance	9.4%	3.75%
Rhythmic changes	daily and seasonal	------

[a] Adapted from Thorington, 1985

[b] Sun (Alt. 77.7°) and sky (clear); June 22, 1979, Tokyo, Japan

FIGURE CAPTIONS

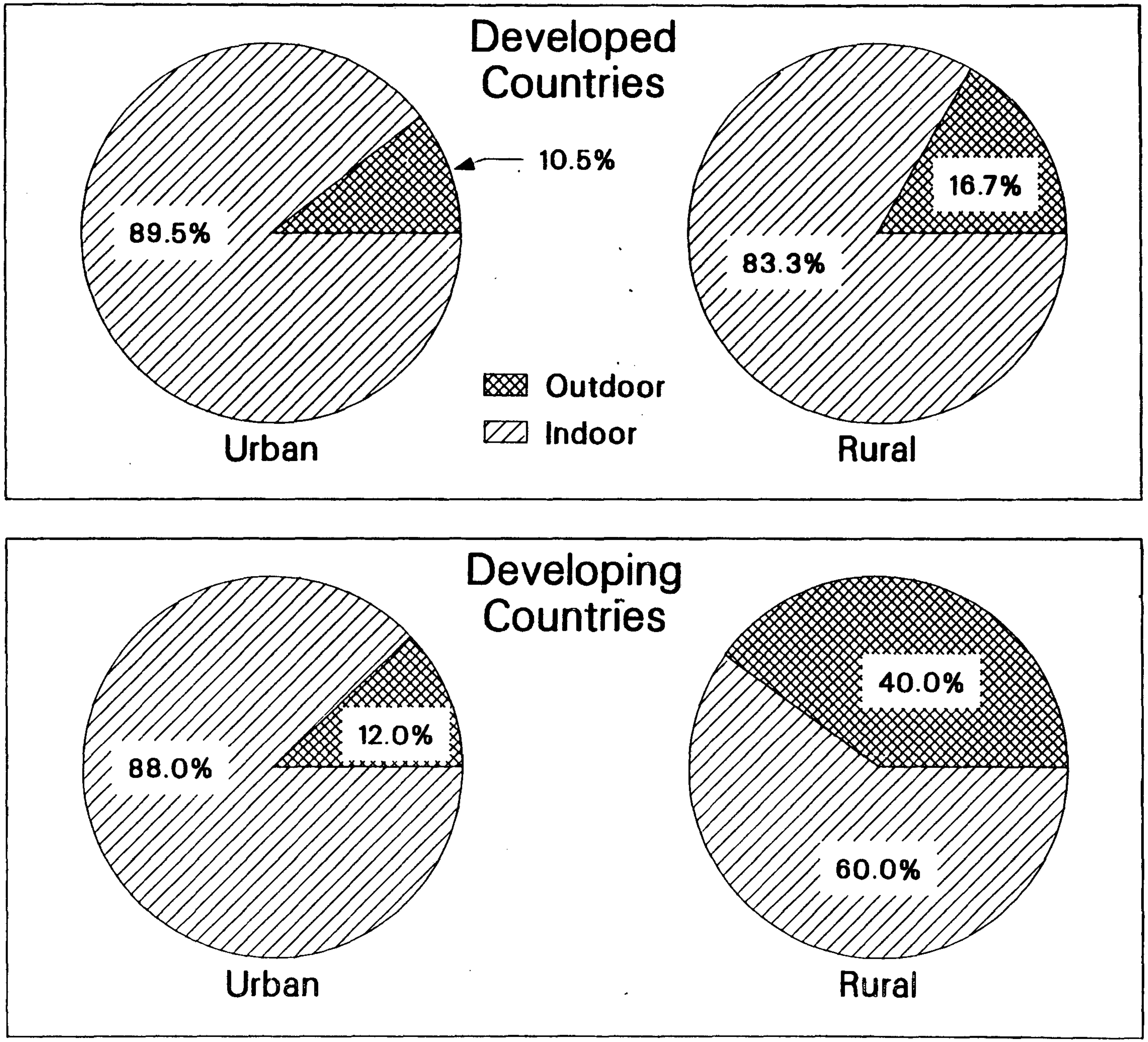
Figure 1. Estimates of the percentages of time spent in indoor and outdoor microenvironments in developed and developing countries (From Smith, 1988).

Figure 2. Variations in Los Angeles smog concentrations measured as ozone in pphm as a function of temperature at North Street in 1985 (Source: Laura Wilson, University of California, Berkeley).

Figure 3. Comparison of estimated probability of suffering a fatal disease from exposure to indoor air pollutants to smoking, occupational hazards, exposure to outdoor pollution, exposures to pollutants in drinking water and food (From Nero, 1988).

Figure 4. Approximate percentage distribution of total global population exposure to particulate air pollution (From Smith, 1988).

Estimates of the Percentages of Time Spent in Indoor and Outdoor Microenvironments



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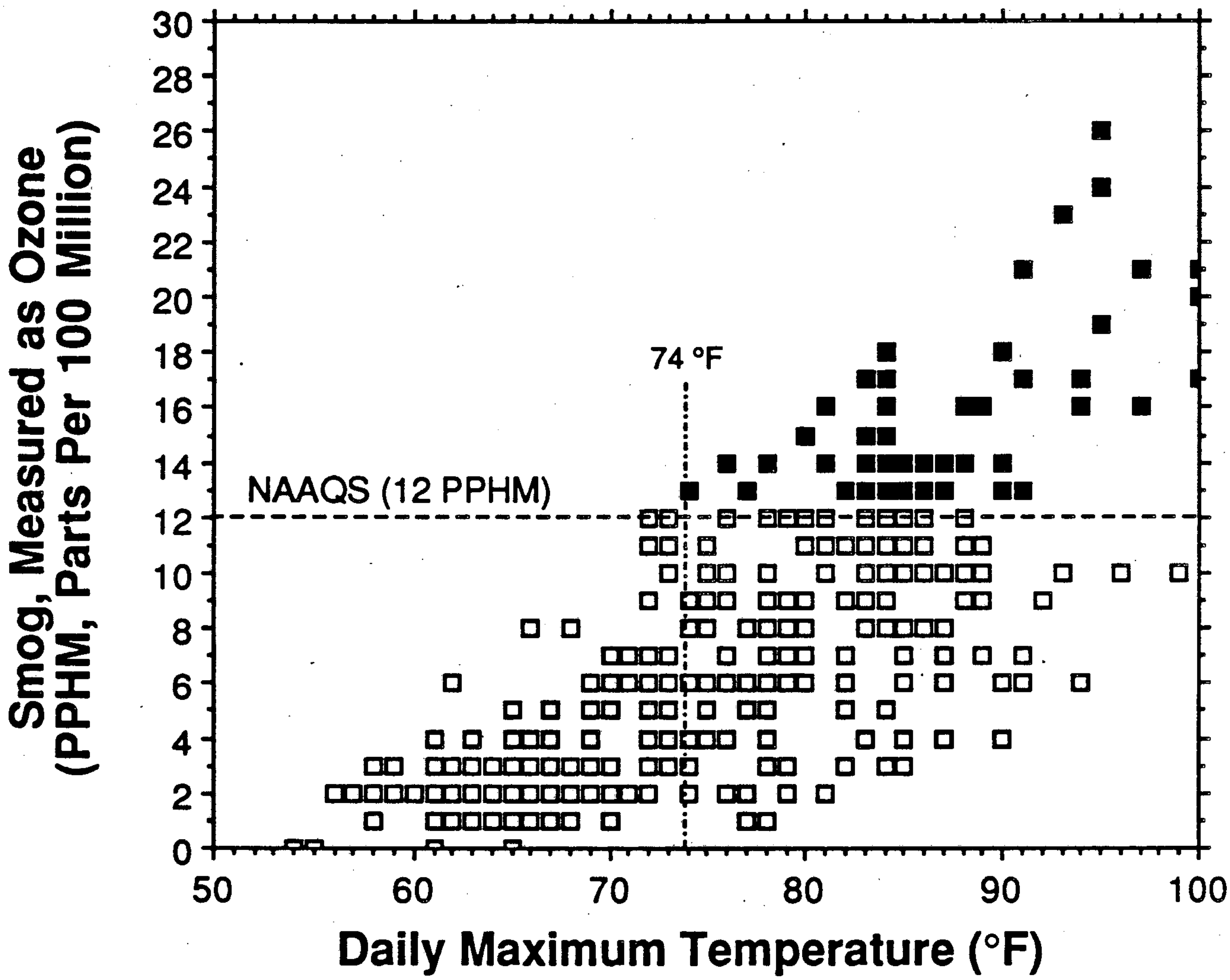
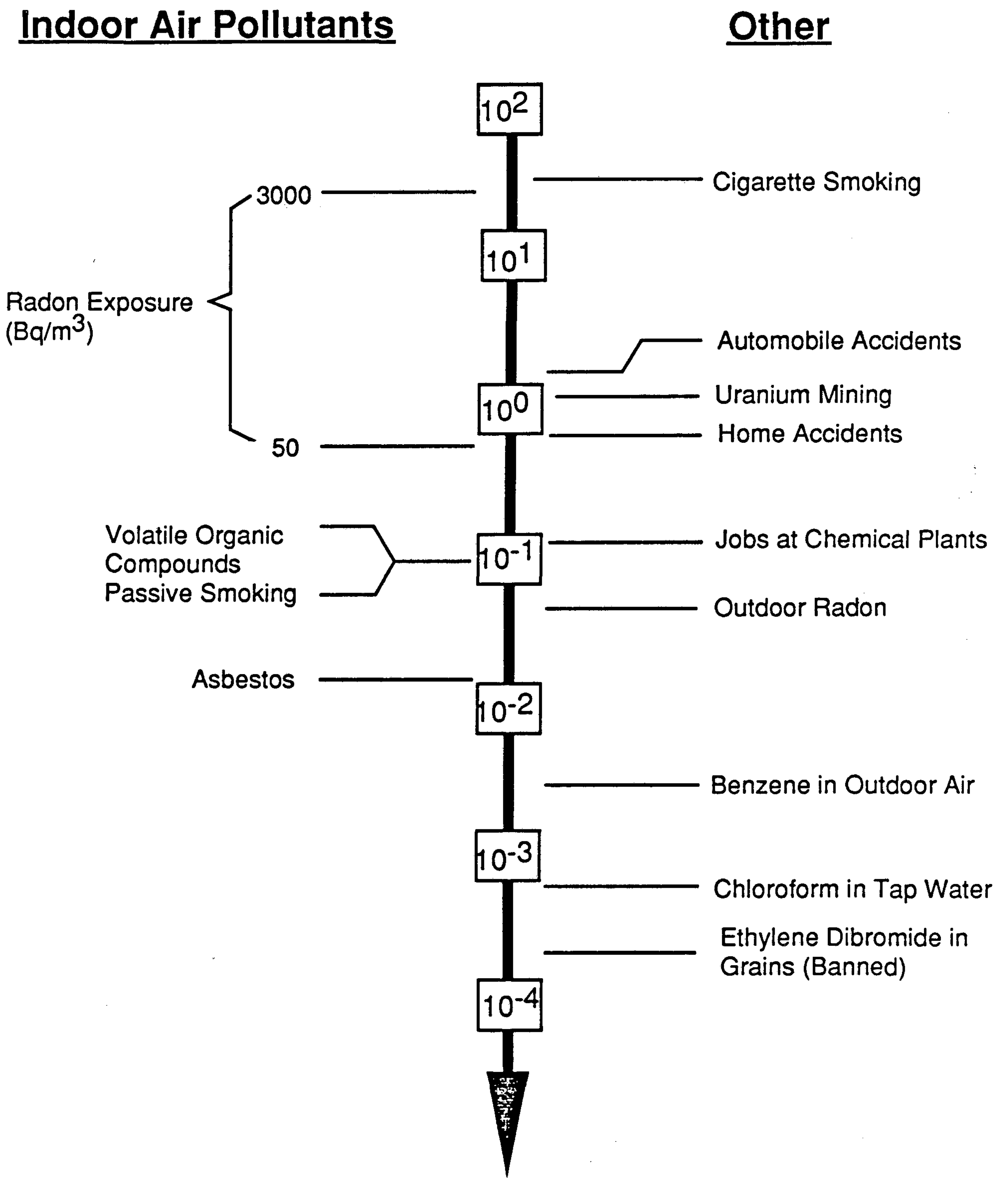

Smog, Measured as Ozone
(PPHM, Parts Per 100 Million)
Daily Maximum Temperature (°F)
74 °F
NAAQS (12 PPHM)
0
2
4
6
8
10
12
14
16
18
20
22
24
26
28
30
50
60
70
80
90
100

Lifetime Risk of Premature Death (%)



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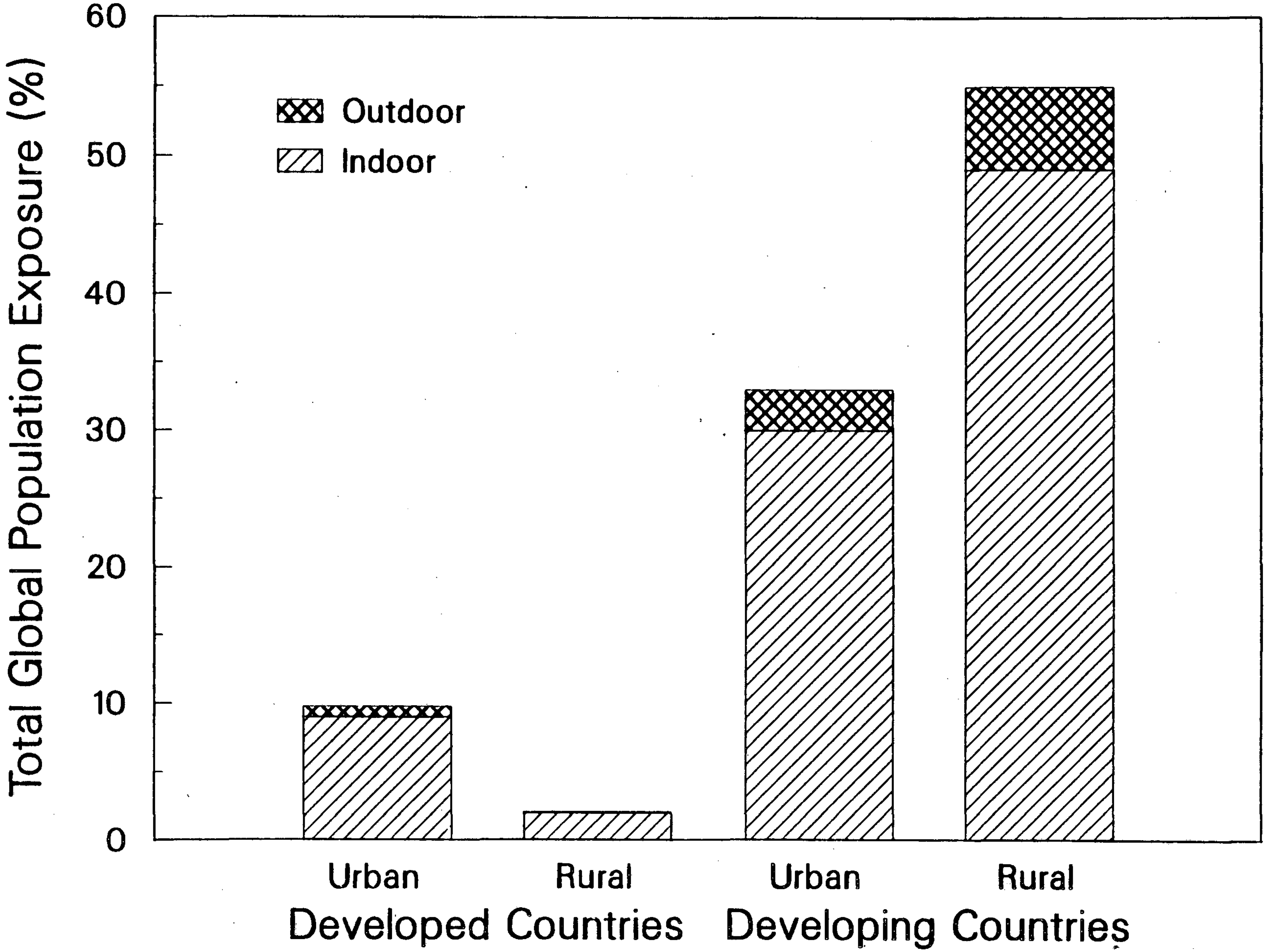
Approximate Percentage Distribution of Total Global Population Exposure to Particulate Air Pollution



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