Health and Productivity Gains from Better Indoor Environments and Their Implications for the U.S. Department of Energy

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A substantial portion of the U.S. population suffers frequently from communicable respiratory illnesses, allergy and asthma symptoms, and sick building syndrome symptoms. We now have increasingly strong evidence that changes in building design, operation, and maintenance can significantly reduce these illnesses. Decreasing the prevalence or severity of these health effects would lead to lower health care costs, reduced sick leave, and shorter periods of illness-impaired work performance, resulting in annual economic benefits for the U.S. in the tens of billions of dollars. Increasing the awareness of these potential health and economic gains, combined with other factors, could help bring about a shift in the way we design, construct, operate, and occupy buildings. The current goal of providing marginally adequate indoor environments could be replaced by the goal of providing indoor environments that maximize the health, satisfaction, and performance of building occupants. Through research and technology transfer, DOE and its contractors are well positioned to help stimulate this shift in practice and, consequently, improve the health and economic well-being of the U.S. population. Additionally, DOE's energy-efficiency interests would be best served by a program that prepares for the potential shift, specifically by identifying and promoting the most energy-efficient methods of improving the indoor environment. The associated research and technology transfer topics of particular relevance to DOE are identified and discussed.

[1]Note that the contents present the views of their authors, not necessarily those of the Department of Energy, RAND, or any other organization with which the authors may be affiliated.

Introduction and Objective

Analyses by Fisk and Rosenfeld (1997) provided the first broad review in the U.S. of the potential to improve both health and productivity through improvements in indoor environments. Subsequent papers (Fisk 2000a, 2000b) have upgraded and updated the analyses. This paper summarizes these prior analyses of the potential improvements in health and associated economic benefits, incorporates a few updates, and discusses the implications for the research and technology transfer programs of the U.S. Department of Energy (DOE). The motivation for this effort is to provide input for strategic planning underway by the DOE. Unlike our prior analyses, this paper does not consider opportunities to directly enhance work performance, through changes in the indoor environment, without an associated improvement in health. The potential to directly enhance productivity will be addressed at this conference in other papers.

Underlying the analyses presented in this paper are three pathways to health-related economic benefits, as illustrated in Figure 1. In all cases, the starting point is a change in building design, operation, and maintenance that improves indoor environmental quality (IEQ) and enhances the health of the building's occupants. Economic benefits may result from: (1) reduced health care costs; (2) reduced sick leave; and (3) a reduction in time when health effects diminish the performance of workers while they are at work. The changes in building design, operation, and maintenance undertaken to improve IEQ may increase or decrease building energy use.

Methods

The basic approach was to review the relevant literature and analyze the key studies showing linkages between indoor environmental factors and health outcomes. Relevant papers were identified through computer-based literature searches, reviews of conference proceedings, and discussions with researchers. Communicable respiratory illnesses, allergies and asthma, and sick building syndrome symptoms were identified as the three categories of health effects in the analyses because their prevalences are influenced by IEQ and the affected populations are very large. Published health studies were reviewed to determine the strength of associations between building-related risk factors (e.g., low ventilation rates) and health outcomes. Expertise in building science and engineering provided information on the potential to diminish the risk factors. With these inputs, plus judgments, the potential reductions in health effects were estimated. The economic costs of these adverse health effects were estimated, primarily by synthesizing and updating the results of previously

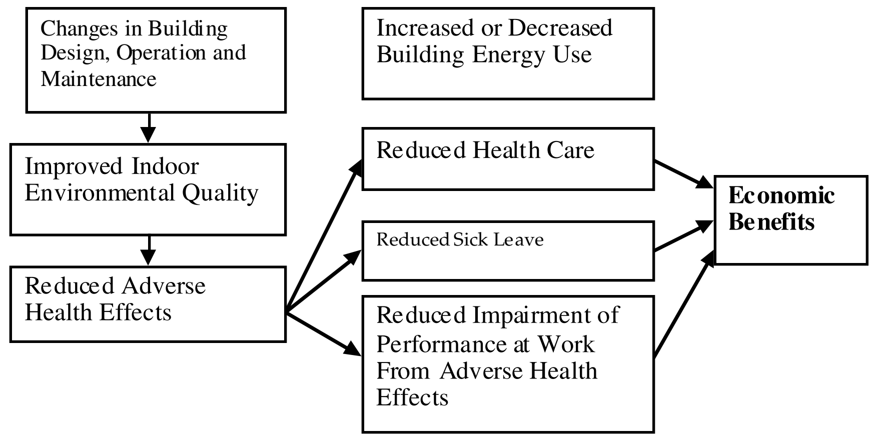

Figure 1—Pathways to Health and Economic Gains

published cost estimates. Prior economic estimates were updated to 1996 to account for general inflation, health care inflation, and increases in population (U.S. Department of Commerce 1997). Finally, the potential annual nationwide health and productivity gains were computed by multiplying the population affected and associated costs by the estimated potential percentage reduction in health effects.

Even with the best of the information currently available, there is a high level of uncertainty with these estimates of the health and associated economic gains attainable from improvements in the indoor environment. In general, the largest source of uncertainty is the degree to which health effects could be reduced through practical changes in building design, operation, and maintenance. A range of estimated gains are provided to reflect this source of uncertainty. For sick building syndrome symptoms, the total costs to society are also uncertain; however, the estimates provided here do not reflect this additional level of uncertainty.

Improvements in the indoor environment depend on changes to building design, operation, maintenance, use, or occupancy. This paper considers whether feasible and practical changes could improve health; however, it does not claim that it will be easy to stimulate the investments or changes in behaviors that are necessary in order to improve IEQ. For example, this paper assumes that it is feasible and practical to restrict indoor tobacco smoking, maintain pets outside of the homes of pet allergic people, improve air filtration systems, prevent low ventilation rates, and reduce water leakage from outdoors to indoors. Realization of the “potential” health and productivity gains identified in this paper will depend on changes in behavior and, in some cases, on financial investments in better building design, operation and maintenance. The expected benefit-to-cost ratios for these measures will often be large because the salaries and benefits of workers typically dominate building energy, maintenance, and lease costs (Woods 1989).

To make this article understandable to a broad audience, the use of potentially unfamiliar statistical terminology has been minimized. For example, as substitutes for the odds ratios or relative risks normally provided in the scientific literature, this article provides estimates of the percentage increases and decreases in outcomes (e.g., health effects) that are expected when building-related risk factors (e.g., mold exposures) are present or absent. Measures of statistical significance are included only within footnotes. The findings reported in this paper would generally be considered to be statistically significant (e.g., the probability that the findings are due to chance or coincidence is generally less than 5%). Appendix 1 of Fisk (2000b) defines the odds ratio, the relative risk, the term "adjusted", and the means of estimating percentage changes in outcomes from odds ratios or relative risks.

After estimating of potential health and productivity gains, this paper discusses their implication for the US Department of Energy. This discussion is based on the author's knowledge of the interrelationships among building energy efficiency, IEQ, and health and on his understanding of DOE's mission and capabilities.

Potential Health and Productivity Gains

For each of the three health categories, the subsequent text starts with a review of the evidence for the linkage between indoor environmental conditions and the health outcomes, follows with a discussion of the populations affected and associated costs, and concludes with estimates of the potential health and productivity gains.

Communicable Respiratory Illness

Evidence of Linkage. We first consider communicable respiratory illnesses transmitted between people, such as influenza and common colds. Building characteristics could change the number of aerosols containing virus or bacteria, e.g., droplet nuclei from coughs and sneezes, that are inhaled, increase or diminish the viability of the inhaled virus or bacteria, or modify the susceptibility of occupants to infection. Consequently, the following building characteristics may theoretically affect the prevalences of respiratory illnesses: efficiency or rate of air filtration; rate of ventilation (i.e., supply of outside air per occupant); amount of air recirculation in ventilation systems, separation between individuals (dependent on occupant density and use of private work spaces); air temperature and humidity (which affect the period of viability of infectious aerosols); and mold levels since molds may increase susceptibility to illness. As discussed in Fisk (2000a), infectious aerosols are thought or known to contribute substantially to transmission of common colds (e.g., rhinovirus infections), influenza, adenovirus infections, measles, and other common respiratory illnesses. Disease transmission due to direct person-to-person contact or to indirect contact via contaminated objects, may be largely unaffected by indoor environmental and building characteristics.

In addition to the theoretical expectations, data are available from several field studies that have examined the association of building characteristics with the prevalence of respiratory illness among building occupants. Two studies were performed in military barracks. A large multi-year investigation by the U.S. Army (Brundage et al. 1988) determined that clinically-confirmed rates of acute respiratory illness with fever were 50% higher among recruits housed in newer barracks with closed windows, low rates of outside air supply, and extensive air recirculation compared to recruits in older barracks with frequently open windows, more outside air, and less recirculation.[2] In another barracks study, Langmuir et al. (1948) compared the rate of respiratory illness with fever among recruits housed in barracks with ultraviolet lights (UV) that irradiated the indoor air near the ceiling (a technology designed to kill infectious bioaerosols) to the rate of respiratory illness among recruits in barracks without UV lights. For the entire study period, the population housed in barracks with UV irradiated air had 23% less respiratory illness.[3]

Several additional studies from a variety of building types provide relevant information on this topic. Jaakkola et al. (1993), found that office workers with one or more roommates were about 20% more likely to have more than two cases of the common cold during the previous year than office workers with no roommates.[4] At an Antarctic station, the incidence of respiratory illness was twice as high in the population housed in smaller (presumably more densely populated) living units (Warshauer et al. 1989). In an older study of New York schools (N.Y. State Commission on Ventilation 1923), there were 70% more

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[2]Adjusted relative risk = 1.51, 95% confidence interval (CI) 1.46 to 1.56.

[3]No test of statistical significance was performed.

[4]Adjusted odds ratio = 1.35 (95% CI 1.00 - 1.82).

respiratory illnesses[5] and 18% more absences from illness[6] in fan-ventilated classrooms compared to window-ventilated classrooms, despite a lower occupant density in the fan-ventilated rooms. Unfortunately, ventilation rates were not measured in the classrooms. Another study investigated symptoms associated with infectious illness among 2598 combat troops stationed in Saudi Arabia during the Gulf War (Richards et al. 1993). The study results suggest that the type of housing (air-conditioned buildings, non-air-conditioned buildings, open warehouses, and tents) influenced the prevalence of symptoms associated with respiratory illness. Housing in air-conditioned buildings (ever versus never housed in an air-conditioned building while in Saudi Arabia) was associated with approximately a 37% greater prevalence of sore throat[7] and a 19% greater prevalence of cough.[8]

Although jails are not representative of other buildings because of severe crowding and residents that are not representative of the general public, disease transmission in jails is an important public health issue and indoor-environmental factors that influence disease transmission in jails may also be important, but less easily recognized, in other environments. Hoge et al. (1994) studied an epidemic of pneumococcal disease in a Houston jail. There were significantly fewer cases of disease among inmates with 7.4 m2 or more of space[9] relative to inmates with less space. The disease attack rate was about 95% higher in the types of jail cells with the highest carbon dioxide concentrations, i.e., the lowest volume of outside air supply per person.[10]

Drinka et al. (1996) studied an outbreak of influenza in four nursing homes located on a single campus. Influenza, confirmed by analyses of nasopharyngeal and throat swab samples, was isolated in 2% of the residents of Building A versus an average of 13% in the other three buildings[11] (16%, 9%, and 14% in Buildings B, C and D, respectively). After correction for the higher proportion of respiratory illnesses that were not cultured in Building A, an estimated 3% of the residents of Building A had influenza, a rate 76% lower than observed in the other buildings.[12] The total number of respiratory illnesses (i.e., influenza plus other respiratory illnesses) per resident was also 50% lower in Building A.

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[5] Difference more than three times probable error.

[6] Difference greater than probable error.

[7] Adjusted odds ratio =1.57 (95% CI 1.32-1.88).

[8] Adjusted odds ratio = 1.33 (95% CI 1.01 - 1.46)

[9] $p=0.03$

[10] Relative risk = 1.95 (95% CI 1.08-3.48).

[11] $p < 0.001$, Cochran-Mantel-Haenszel statistics

[12] $p < 0.001$, chi-square

Vaccination rates and levels of nursing care did not differ among the buildings. The authors suggested that architectural factors were the cause of the lower infection rate in Building A. The ventilation system of Building A supplied 100% outside air to the building (eliminating mechanical recirculation) while the ventilation systems of the other buildings provided 30% or 70% recirculated air. The Building A ventilation system also had additional air filters. Finally, the public areas of Building A were larger (per resident), reducing crowding that may facilitate disease transmission.

Milton et al. (2000) studied the association of the rate of outside air supply with the rate of absence from work caused by illness in 3720 workers located in 40 buildings with a total of 110 independently-ventilated floors. While absence is not synonymous with respiratory disease, a substantial proportion of short-term absence from work caused by illness results from acute respiratory illness. Ventilation rates were estimated based on ventilation system design, occupancy, and selected end-of-day carbon-dioxide measurements, and buildings were classified as moderate ventilation (~ 12 L s-1 per occupant) or high ventilation (~24 L s-1 per occupant). The absence rate, controlling for age, gender, seniority, crowding, and type of workspace was 35% lower in the high-ventilation buildings.

The association of mold problems in buildings with the incidence of respiratory infections has been investigated in a few studies. One study (Husman et al. 1993, Husman 1996) compared the rates of acute respiratory infection in 158 residents of apartments with verified mold problems to the rates of infection in 139 residents of apartments without mold problems. Approximately twice as many residents of the moldy apartments reported at least one acute respiratory infection during the previous year.[13] A complex multi-stage study examined the association of high mold exposures within day-care centers with common colds as well as other health outcomes in children (Koskinen et al. 1995, 1997) with inconclusive results (i.e., one comparison suggests that mold significantly increased serious persistent respiratory infections while other comparisons found small statistically insignificant decreases in common colds with higher mold exposure.) The recent evidence that mold exposures may adversely affect immune system function (Dales et al. 1998) is consistent with the findings of a positive association between molds and respiratory infections.

Population Affected and Cost of Communicable Respiratory Illness. Virtually everyone is affected by communicable respiratory illnesses. Averaging data from

[13]Relative risk is 2.2, 95% CI is 1.2 to 4.4, adjusted for age, sex, smoking and atopy

1992 through 1994, the civilian non-institutional population experienced 43.3 common colds and 25.7 cases of influenza per 100 population (US Department of Commerce 1997), for a total of 0.69 illnesses per person per year.

The obvious costs of respiratory illness include health care expenses and the costs of absence from work. Additionally, respiratory illnesses may cause a performance decrement at work. In controlled experiments, Smith (1990) has shown that viral respiratory illnesses, even sub-clinical infections, can adversely affect performance on several computerized and paper-based tests that simulate work activities. The decrement in performance can start before the onset of symptoms and persist after symptoms are no longer evident.

Estimates of the productivity losses associated with respiratory illness are based on periods of absence from work and restricted activity days as defined in the National Health Interview Survey (U.S. Department of Health and Human Services 1994). In the U.S., four common respiratory illnesses (common cold, influenza, pneumonia, and bronchitis) cause about 176 million days lost from work and an additional 121 million work days of substantially restricted activity (Dixon 1985, adjusted for population gain). Assuming a 100% and 25% decrease in productivity on lost-work and restricted-activity days, respectively, and a $39,200 average annual compensation (U.S. Department of Commerce 1997), the annual value of lost work is approximately $34 billion.[14] The annual health care costs for upper and lower respiratory tract infections total about $36 billion (Dixon 1985, adjusted for population gain and health care inflation). Thus, the total annual cost of respiratory infections is approximately $70 billion. Neglected costs include the economic value of reduced housework and of absence from school.

Potential Savings. Without being able to substantially change the building-related factors that influence disease transmission, we cannot realize these health care cost savings and productivity gains. A number of existing, relatively practical building technologies, such as increased ventilation, reduced air recirculation, improved filtration, ultraviolet disinfection of air, and reduced space sharing (e.g., shared office), and reduced occupant density have the theoretical potential of reducing inhalation exposures to infectious aerosols by more than a factor of two.

The studies cited above suggest that changes in building characteristics and ventilation could reduce indexes of respiratory illness by 15% (absence from school) to 76% (influenza in nursing homes), with the strongest study (Brundage

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[14] A similar estimate, $39 billion, is obtained based on the information in Garabaldi (1985)

et al. 1988) suggesting that a 33% reduction is possible. The amount of time spent in a building should influence the probability of disease transmission within the building. If efforts to reduce disease transmission were implemented primarily in commercial and institutional buildings[15] that people occupy approximately 25% of the time, smaller reductions in respiratory illness would be expected in the general population than indicated by the building-specific studies. To adjust the reported decreases in respiratory illness for time spent in buildings, we estimated the percentage of time that occupants spend in each type of building (100% of time in jails and nursing home, 66% in barracks and housing, and 25% in offices and schools) and assumed that the magnitude of the influence of a building factor on the incidence of respiratory illness varies linearly with time spent in the building. After this adjustment and neglecting the Gulf War study involving some housing in tents and warehouses, the nine remaining studies cited above yield 11 estimates of potential decreases in metrics for respiratory illness (some studies had multiple outcomes such as influenza and total respiratory infections), ranging from 9% to 41% with an average of 19% (see Figure 2). Considering only the studies with explicit respiratory illness outcomes

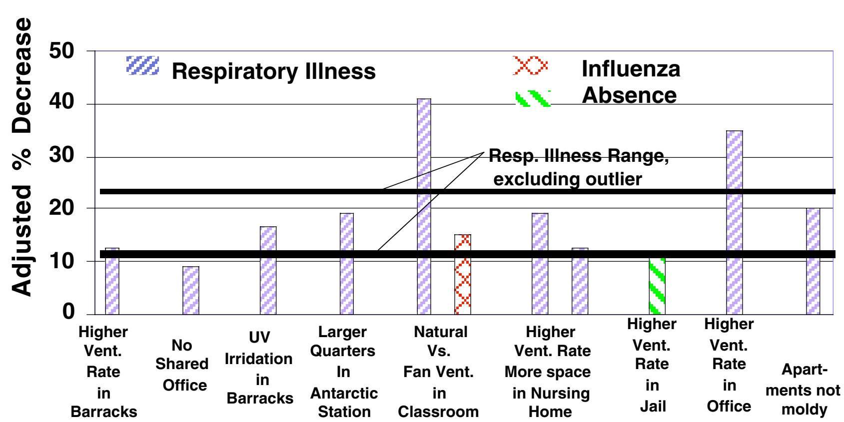

Figure 2. Estimated decreases in respiratory illness from changes in building characteristics.

Figure 2—Estimated Decreases in Respiratory Illness from Changes in Building Characteristics

[15]There are no technical barriers to implementation of similar measures in residences; however, business owners will have a stronger financial incentive to take action than home owners.

(i.e., excluding the study with an absence outcome) results in nine estimates of decreases in respiratory illness, adjusted for time in building, ranging from 9% to 41% with an average of 18%. The range is 9% to 20%, if the outlier value of 41% (illness in schools) is excluded. This narrower range is adopted, i.e., 9% to 20%, for the potential reduction in respiratory illness. With this estimate and 0.69 cases of common colds and influenza per person per year), approximately, 16 to 37 million cases of common cold or influenza would be avoided each year in the US. The corresponding range in the annual economic benefit is $6 billion to $14 billion.

Allergies and Asthma

Linkage. Symptoms of allergies and of asthma may be triggered by a number of allergens in indoor air including those from house dust mites, pets, fungi, insects, and pollens (Committee on Health Effects of Indoor Allergens 1993). Allergens are considered a primary cause of the inflammation that underlies asthma (Platts-Mills 1994). There is evidence (e.g., Arshad et al. 1992, Wahn et al. 1997) that lower exposures to allergens during infancy or childhood can reduce the sensitization to allergens. Asthma symptoms may also be evoked by irritating chemicals, including environmental tobacco smoke (Evans et al. 1987). Viral infections, which may be influenced by building factors, also appear to be strongly linked to exacerbations of asthma, at least in school children. A recent study of 108 children, age 9 to 11, found a strong association of viral infections with asthma exacerbation (Johnston et al. 1995). Viral infections were detected in 80% to 85% of asthmatic children during periods of asthma exacerbation. During periods without exacerbation of asthma symptoms, only 12% of the children had detectable viral infections.[16]

Building factors most consistently and strongly associated with asthma and allergic respiratory symptoms include moisture problems, indoor tobacco smoking, house dust mites, molds, cats and dogs, and cockroach infestation (Committee on the Assessment of Asthma and Indoor Air 1999, Committee on Health Effects of Indoor Allergens 1993). Platts-Mills and Chapman (1987) provide a detailed review of the substantial role of dust mites in allergic disease. In a recent review of the association of asthma with indoor air quality by the National Academy of Sciences (Committee on the Assessment of Asthma and Indoor Air 1999), the prevalence of asthma or related respiratory symptoms is increased by approximately a factor of two[17] among occupants of homes or

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[16]The difference between infection rates is statistically significant, $p< 0.001$

[17]Neglecting one study in the review with a very high odds ratio of 16.

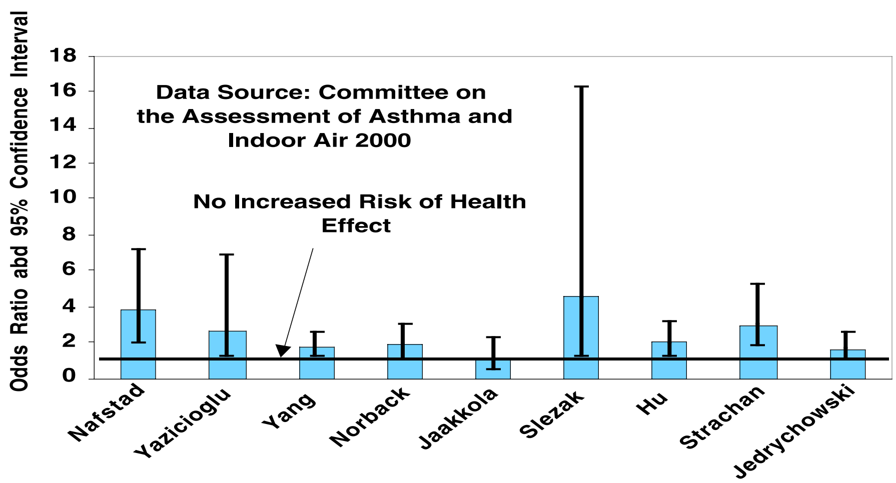

Figure 3. Association of Asthma-Related Health Effects with Dampness Problems or Visible Molds

schools with evidence of dampness problems or molds (Figure 3). In the same review, environmental tobacco smoke exposure, indicated by parental smoking, is typically associated with increases in asthma symptoms or incidence by 20% to 40%.

Data from few office-based studies are available for asthma and allergy associations with indoor environmental conditions. In case studies, moisture and related microbiological problems have been linked to respiratory symptoms in office workers (Division of Respiratory Disease Studies 1984, Hoffmann et al. 1993). In a study of office workers[18] (Menzies et al. 1988), higher relative humidity, higher concentrations of alternaria (a mold) allergen in air, and higher dust mite antigen in floor dust were associated with a higher prevalence of respiratory symptoms.

Overall, the evidence of a linkage between the quality of the indoor environment and the incidence of allergic and asthma symptoms is strong. Additionally, the exposures that cause allergic sensitization often occur early in life and are likely to occur indoors; consequently, the quality of indoor environments may also influence the proportion of the population that is allergic or asthmatic.

Population Affected and Cost of Allergies and Asthma. Approximately 20% of the U.S. population have allergies to environmental antigens (Committee on Health Effects of Indoor Allergens 1993) and approximately 6% have asthma

[18]This was a case-control study of ~ 17% of all workers in the buildings.

(Rappaport and Boodram 1998). Drawing upon five recent papers, Fisk (2000b) has estimated that the annual costs for 1996 of allergies and asthma in the U.S. is $15 billion. Approximately $10 billion are health care costs and the remaining costs are indirect costs, for example the costs of lost work and school. A significant portion of the costs of allergies and asthma reflect the burden of these diseases in children.

Potential Savings from Changes in Building Factors. There are three general approaches for reducing allergy and asthma symptoms via changes in buildings and indoor environments. First, one can control the indoor sources of the agents that cause symptoms (or that cause initial allergic sensitization). For example, indoor tobacco smoking can be restricted to isolated separately-ventilated rooms, or prohibited entirely. Pets can be maintained outside of the homes of individuals that react to pet allergens. Perhaps even more broadly effective are measures that reduce the growth of microorganisms indoors. Changes in building design, construction, operation, and maintenance could reduce water leaks and moisture problems and decrease indoor humidities (where humidities are normally high), leading to a reduction in dust mites and molds in buildings. Known reservoirs for allergens, such as carpets for dust mite allergen, can be eliminated or modified. Improved cleaning of building interiors and HVAC systems can also limit the growth or accumulation of allergens indoors. There are no major technical obstacles to these measures.

The second general approach for reducing allergy and asthma symptoms is to use air cleaning systems or increased ventilation to decrease the indoor airborne concentrations of the relevant pollutants. Many of the relevant exposures are airborne particles. Technologies are readily available for reducing indoor concentrations of airborne particles generated indoors. Better filtration of the outside air entering mechanically-ventilated buildings can also diminish the entry of outdoor allergens into buildings. Filtration is likely to be most effective for the smaller particles linked to allergies and asthma, such particles from tobacco smoke. Allergens that are large particles, e.g., from dust mites, have high gravitational settling velocities and are less effectively controlled by air filtration.

The influence of particle air cleaners on symptoms of allergies and asthma is reviewed by Committee on the Assessment of Asthma and Indoor Air (1999), and one more recent study is provided by van der Heide (1999). Many published studies have important limitations such as small air cleaners, a small number of subjects, or a focus on dust mite allergies which may be poorly controlled with air cleaners due to the large size and high settling velocities of dust mite allergens. Five of twelve studies involving subjects with perennial allergic disease or asthma reported statistically significant improvements in symptoms or airway hyperresponsiveness, or reduced use of medication when air cleaners were used. In six of seven studies, seasonal allergic or asthma symptoms were significantly reduced with air cleaner use. Subjects were blinded, i.e., unaware of air cleaner operation, in only two of these studies involving seasonal symptoms; thus, results could have been biased by the subjects' expectations.

Because viral respiratory infections will often exacerbate asthma symptoms, a third approach for reducing asthma symptoms is to modify buildings in a manner that reduce viral respiratory infections among occupants, as discussed previously.

With the available data, the magnitude of the potential reduction in allergy and asthma symptoms is quite uncertain, but some reduction is clearly possible using practical measures. The subsequent estimate is based on two considerations: 1) the degree to which indoor allergen concentrations and concentrations of irritating chemicals can be reduced, and 2) the strength of the reported associations between symptoms and changeable building and IEQ factors. Regarding the first consideration, significant reductions in allergy and asthma symptoms would not be expected unless it was possible to substantially reduce indoor concentrations of the associated allergens and irritants. From engineering considerations, it is clear that concentrations of many allergens could be reduced very substantially. Filtration systems, appropriately sized, should be capable of reducing concentrations of the smaller airborne allergens by approximately 75%. Some of the source control measures, such as elimination of water leaks, control of indoor humidities, reduction or elimination of indoor smoking and pets, and improved cleaning and maintenance are likely to result in much larger reductions in the pollutants that contribute to allergies and asthma.

As discussed above, several cross-sectional or case-control studies have found that building-related risk factors, such as moisture problems and mold or environmental tobacco smoke, are associated with 20% to 100% increases in allergy and asthma symptoms, implying that 16% to 50% reductions in symptoms are possible by eliminating these risk factors. However, the complete elimination of these risk factors is improbable. Assuming that it is feasible and practical to reduce these risks by a factor of two, leads to a 8% to 25% estimate of the potential reduction in allergy and asthma symptoms. With this estimate, the annual savings would be ~$1 to ~$4 billion. Control measures can be targeted at the homes or offices of susceptible individuals, reducing the societal cost.

Sick Building Syndrome Symptoms

Linkage. Characteristics of buildings and indoor environments have been linked to the prevalence of acute building-related health symptoms, often called sick-building syndrome (SBS) symptoms, experienced by building occupants. SBS symptoms include irritation of eyes, nose, and skin, headache, fatigue, and difficulty breathing. Although psychosocial factors such as job stress influence SBS symptoms, many building factors are also known or suspected to influence these symptoms including: type of ventilation system; rate of outside air ventilation; level of chemical and microbiological pollution; and indoor temperature and humidity (Mendell 1993; Sundell 1994; Menzies and Bourbeau 1997, Seppanen et al. 1999). In the review by Seppanen et al. (1999), 21 of 27 assessments meeting study quality criteria found lower ventilation rates to be significantly associated with an increase in at least one SBS symptom (Figure 4). Extrapolating from one of the largest studies, a 5 L s-1 increase in ventilation rates in US office buildings would reduce the proportion of office workers with frequent upper respiratory symptoms from 26% to 16%. For eye symptoms, the corresponding reduction would be from 22% to 14%. In a set of problem buildings studied by (Sieber et al. 1996), SBS symptoms were associated with evidence of poorer ventilation system maintenance or cleanliness. For example, debris inside the air intake and poor drainage from coil drain pans were associated with a factor of three increase in lower respiratory symptoms.[19] In the same study, daily vacuuming was associated with a 50% decrease in lower respiratory symptoms.[20] In some, but not all, controlled experiments, SBS symptoms have been reduced through practical changes in the environment such as increased ventilation, decreased temperature, and improved cleaning of floors and chairs (Mendell 1993, Menzies and Bourbeau 1997, Seppanen et al. 1999). Therefore, SBS symptoms are clearly linked to features of buildings and indoor environments.

Population Affected and Cost of SBS Symptoms. SBS symptoms are most commonly reported by office workers and teachers that make up about 50% of the total workforce (64 million workers[21]). In a modest fraction of buildings, often referred to as “sick buildings”, symptoms become severe or widespread, prompting investigations and remedial actions. The term “sick building

[19]For debris in air intake, relative risk = 3.1 and 95% CI = 1.8 to 5.2 For poor or no drainage from drain pans, relative risk = 3.0 and 95% CI = 1.7 to 5.2

[20]Relative risk = 0.5, 95% CI = 0.3 to 0.9

[21]Based on statistical data of employed civilians by occupation (US Department of Commerce 1997), there are approximately 63 million civilian office workers plus teachers (49.6% of the civilian workforce). Assuming that 50% of the 1.06 million active duty military personnel are also office workers, the total is approximately 63.5 million.

Figure 4. Ventilation rates per person and SBS symptoms. (Data source: Seppanen et al. 1999)

Author	Yr.	Relative risk or (odds ratio)
Jaakkola	91a	1.1
Gamble	86	1.8
Gamble	86	2.4
Groes	95	N/A
Jaakkola	91b	1.3
Jaakkola	91b	1.2
Jaakkola	91b	1.1
Jaakkola	95	5.4-37
Cochet	95	1.7 - 3.8
Sundell	94	(2-3)
Ruotsalainen	94	2.8
Sundell	94a	N/A
Stenberg	94	(1.87)
Wu	96	N/A
Wu	96	N/A
Sundell	94a	N/A
Jaakkola	91a	1.1
Sundell	94b	(1.8)
Jaakkola	95	5.0-6.0
Jaakkola	91a	1.1
Nordström	95a	(1.9-2.6)
Jaakkola	94	0.35-0.46
Jaakkola	91a	N/A
Wyon	92	N/A
Menzies	93a	0.8-1.2
Wyon	92	N/A
Jaakkola	95	4.2-5.2

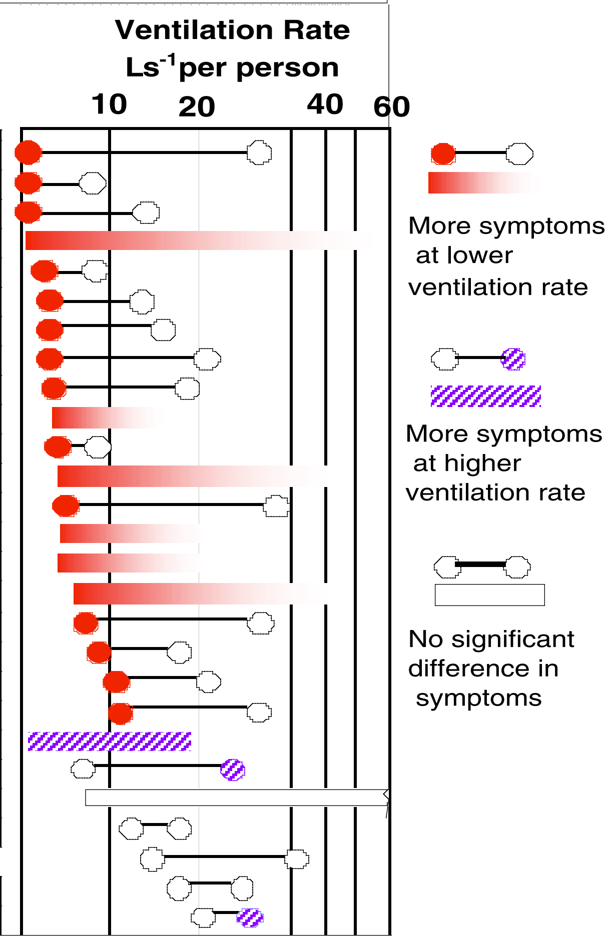

Figure 4—Ventilation Rates per Person and SBS Symptoms

syndrome" is widely used in reference to the health problems in these buildings. However, the syndrome appears to be the visible portion of a broader phenomenon. These same symptoms are experienced by a significant fraction of workers in "normal" office buildings that have no history of widespread complaints or investigations (e.g., Fisk et al. 1993; Nelson et al. 1995, Brightman et al. 1997), although symptom prevalences vary widely among buildings. The most representative data from US buildings, obtained in a 56-building survey (that excluded buildings with prior SBS investigations) found that 23% of office workers reported two or more frequent symptoms that improved when they were away from the workplace. (HS Brightman, Harvard School of Public Health, Personal Communication). Applying this percentage to the estimated number of U.S. office workers and teachers (64 million), the number of workers frequently affected by at least two SBS symptoms is 15 million.

SBS symptoms are a hindrance to work and are associated with absences from work (Preller et al. 1990) and visits to doctors. When SBS symptoms are particularly disruptive, investigations and maintenance may be required. There are financial costs to support the investigations and considerable effort is typically expended by building management staff, by health and safety personnel and by building engineers. Responses to SBS have included costly changes in the building, such as replacement of carpeting or removal of wall coverings to remove molds, and changes in the building ventilation systems. Some cases of SBS lead to protracted and expensive litigation. Moving employees imposes additional costs and disruptions. Clearly, these responses to SBS impose a significant societal cost, but information is not available to quantify this cost.

Calculations indicate that the costs of small decreases in productivity from SBS symptoms are likely to dominate the total SBS cost. Limited information is available in the literature that provides an indication of the influence of SBS symptoms on worker productivity. In a New England Survey, described in EPA's 1989 report to Congress (U.S. Environmental Protection Agency, 1989), the average self-reported productivity loss due to poor indoor air quality was 3%. Woods et al. (1987) completed a telephone survey of 600 U.S. office workers and 20% of the workers reported that their performance was hampered by indoor air quality, but the study provided no indication of the magnitude of the productivity decrement. In a study of 4373 office workers in the U.K. by Raw et al. (1990), workers who reported higher numbers of SBS symptoms during the past year also indicated that physical conditions at work had an adverse influence on their productivity. Based on the data from this study, the average self-reported productivity decrement for all workers, including those without SBS symptoms, was about 4%.[22] In an experimental study (Menzies et al. 1997b), workers provided with individually-controlled ventilation systems reported fewer SBS symptoms and also reported that indoor air quality at their workstation improved productivity by 11% relative to a 4% decrease in productivity for the control population of workers.[23]

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[22]The data indicate a linear relationship between the number of SBS symptoms reported and the self-reported influence of physical conditions on productivity. A unit increase in the number of symptoms (above two symptoms) was associated with approximately a 2% decrease in productivity. Approximately 50% of the workers reported that physical conditions caused a productivity decrease of 10% or greater; 25% of workers reported a productivity decrease of 20% or more. Based on the reported distribution of productivity decrement (and productivity increase) caused by physical conditions at work, the average self-reported productivity decrement is about 4%.

[23]$P < 0.05$ for the reduction in SBS symptoms and $p < 0.001$ for the self-reported change in productivity.

In addition to these self-reported productivity decrements, measured data on the relationship between SBS symptoms and worker performance are provided by Nunes et al. (1993). Workers who reported any SBS symptoms took 7% longer to respond in a computerized neurobehavioral test[24] and error rates in this test decreased non-significantly (the18% decrease was not significant). In a second computerized neurobehavioral test, workers with symptoms had a 30% higher error rate[25] but response times were unchanged. Averaging the percent changes from the four performance outcomes yields a 14% decrement in performance among those with SBS symptoms. Multiplying by the estimated 23% of office workers with 2 or more frequent symptoms yields a 3% average decrease in performance.

Other objective findings were obtained in a study of 35 Norwegian classrooms. Higher concentrations of carbon dioxide, which indicate a lower rate of ventilation, were associated with increases in SBS symptoms and also with poorer performance in a computerized test of reaction time[26] (Myhrvold et al. 1996); however, the percentage change in performance was not specified. Renovations of classrooms with initially poor indoor environments, relative to classrooms without renovations, were associated with reduced SBS symptoms and with improved performance by 5.3% in the reaction time tests[27] (Myhrvold and Olsen 1997).

Investigations by Wargocki et al. (1999, 2000, 2000a) and Lagercrantz et al. (2000) provide additional objective evidence that SBS symptoms reduce productivity. In a series of laboratory-based, blinded, controlled, randomized experimental studies, the health symptoms and satisfaction with of IEQ of workers were monitored along with the workers' performance of work-related tasks including: typing, addition, proof reading, and creative thinking. The laboratory had the appearance of a normal office but enabled precise control of all environmental parameters. Some experiments were performed with and without a pollutant source (a 20 year old carpet) placed in the laboratory behind a visual screen. Other experiments varied the outside air ventilation rate with the carpet present. The study design controlled for the effects on performance of learning when tasks were repeated. These studies have shown that removing the pollutant

[24] $p < 0.001$

[25] $p = 0.07$

[26] Correlation coefficient = 0.11 and P value = 0.009 for performance versus carbon dioxide. Correlation coefficient = 0.20 and P value = 0.000 for performance versus a score for headache, heavy headed, tiredness, difficulty concentrating, and unpleasant odor. Correlation coefficient = 0.11 and P value = 0.008 for performance versus a score for throat irritation, nose irritation, runny nose, fit of coughing, short winded, runny eyes. Correlation coefficients are controlled for age.

[27] Measures of statistical significance are not included in paper.

source (carpet) or increasing ventilation rates with the pollutant source present were associated with increased satisfaction with indoor air quality,[28] decreases in some SBS symptoms,[29] and increases in performance in text typing, proof reading, and addition.[30] Considering these three work tasks, these studies suggest that doubling of the ventilation rates increase overall performance by 1.9% (Wargocki et al. 2000a). Subsequent analyses indicated that the work performance improved only when the intensity of SBS symptoms diminished and identified a 7% improvement in the score on a creative thinking test[31] as the ventilation rates increased from 3 to 10 L s-1 per person (Wargocki et al. 2000b).

The estimate of the productivity loss from SBS symptoms must be based on the limited information available. The self-reports discussed above suggest a productivity decrease, averaged over the entire work population, of approximately 4% due to poor indoor air quality and physical conditions at work. Although SBS symptoms seem to be the most common work-related health concern of office workers, some of this self-reported productivity decrement may be a consequence of factors other than SBS symptoms. Also, dissatisfied workers may have provided exaggerated estimates of productivity decreases. The objective data reviewed above suggest that SBS symptoms are associated with decrements on the order of 2% to 3%. Based on these data, we assume a productivity decrease caused by SBS equal to 2%, recognizing that this estimate is highly uncertain. This 2% estimate is the basis for subsequent economic calculations.

SBS symptoms are primarily associated with office buildings and other non-industrial indoor work places such as schools. According to Traynor et al. (1993), office workers are responsible for approximately 50% of the US annual gross national product. Statistical data on the occupations of the civilian labor force are roughly consistent with this estimate (US Department of Commerce 1997), i.e., 50% of workers have occupations that would normally be considered office work or teaching. Since the gross domestic product (GDP) of the US in 1996 was $7.6 trillion (US Department of Commerce 1997), the GDP associated with office-type work is approximately $3.8 trillion. Multiplying the number of office workers and teachers (64 million) by the annual average compensation for all workers

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[28] For pollutant source removal, $P < 0.001$ and $P = 0.062$ in two studies. For ventilation rate increase $P = 0.010$. (Wargocki et al 2000a)

[29] For pollutant source removal $p < 0.04$ for severe headache in Wargocki (1999), $p < 0.02$ for dizziness in Lagercrantz et al. (2000), $p < 0.04$ for difficulty in thinking clearly in Lagercrantz et al. (2000)

[30] $P = 0.0002$ for text typing, $P = 0.056$ for addition, $P = 0.08$ for proof reading (Wargocki et al 2000a)

[31] $P = 0.046$

($39.2K) results in a roughly similar estimate of $2.5 trillion. Averaging these two estimates yields $3.2 trillion. Based on the estimated 2% decrease in productivity caused by SBS symptoms, the annual nationwide cost of SBS symptoms is on the order of $60 billion.

Potential Savings from Changes in Building Factors. Because multiple factors, including psychosocial factors, contribute to SBS symptoms, we cannot expect to eliminate SBS symptoms and SBS-related costs by improving indoor environments. However, strong evidence cited by Mendell (1993), Sundell (1994), and Seppanen et al. (1999) of associations between SBS symptoms and building environmental factors, together with our knowledge of methods to change building and environmental conditions, indicate that SBS symptoms can be reduced. As discussed, many SBS studies[32] have found individual environmental factors and building characteristics to be associated with changes of about 20% to 50% in the prevalence of individual SBS symptoms or groups of related symptoms.[33] A smaller number of studies have identified a few building-related factors to be associated with an increase in symptoms by a factor of two or three (e.g., Jaakkola and Miettinen 1995, Sieber et al. 1996). The review by Seppanen et al. (1999) suggests that a 5 L s-1 per person increase in building ventilation rates in the building stock would decrease prevalences of upper respiratory and eye symptoms by ~35%.

In summary, the existing evidence suggests that substantial reductions in SBS symptoms, on the order of 20% to 50%, should be possible through improvement in individual indoor environmental conditions. Multiple indoor environmental factors can be improved within the same building. For the estimate of cost savings, we will assume that a 20% to 50% reduction in SBS symptoms is practical in office buildings. The corresponding annual productivity increase is on the order of $10 to $30 billion.

The Cost of Improving Indoor Environments

In two example calculations, Fisk (2000a) compares the cost of increasing ventilation rates and increasing filter system efficiency in a large office building

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[32] Most of these studies have taken place in buildings without unusual SBS problems, thus, we assume that the reported changes in symptom prevalences with building factors apply for typical buildings.

[33] Adjusted odds ratios (ORs) for the association of symptom prevalences to individual environmental factors and building characteristics are frequently in the range of 1.2 to 1.6. Assuming a typical symptom prevalence of 20%, these ORs translate to risk ratios of approximately 1.2 to 1.5, suggesting that 20% to 50% reductions in prevalences of individual SBS symptoms or groups of symptoms should be possible through changes in single building or indoor environmental features.

with the productivity gains expected from reductions in health effects. The estimated benefit-to-cost ratio is 14 and 8 for increased ventilation and better filtration, respectively. Similar calculations by Milton (2000) result in a benefit-to-cost ratios of three to six for increased ventilation, neglecting the benefits of reduced health care costs which are about half of the total benefit. For many other measures that should increase productivity, we would expect similarly high benefit-to-cost ratios. For example, preventing or repairing roof leaks should diminish the need for building repairs in addition to reducing allergy and asthma symptoms. Also, some measures, such as excluding indoor tobacco smoking or maintaining pets outdoors of the houses of asthmatics, have negligible financial costs.

Other changes in buildings that have been associated with improved health may have higher costs than increases in ventilation rate, improved filtration, minimizing pollutant sources, and better maintenance. For example, reducing occupant density by a factor of two would increase building construction or lease costs by a factor of two and also considerably increase energy costs per occupant. However, even such changes to buildings may be cost effective in some situations because annual salaries plus benefits are approximately 50 times larger than annualized construction costs or rent (Woods 1989).

Implications for the U.S. Department of Energy

A Scenario for High Performance Buildings

The enormous health cost resulting from our current way of designing, constructing and operating buildings poses a major societal challenge. How can we design and operate buildings that promote health and productivity? How can we improve our homes, workplaces, schools, hospitals and other buildings so they are positive environments for the users? Fanger (2000) has suggested a possible paradigm shift. Over the next two decades, the current goal of providing an adequate indoor environment may be replaced by the goal of providing excellent indoor environments that maximize the health, satisfaction, and performance of building occupants. Factors underlying such a paradigm shift include the increasing affluence of the U.S. population, increased expectations for excellent health, the desire to contain health care costs, and the rapidly increasing evidence that IEQ affects health and productivity. Incorporation of IEQ issues in the green building movement and the increasing use of environmental consultants in new building projects may be the visible start of this paradigm shift. If this shift occurs, there will be significant changes to the designs, furnishings, operation, and maintenance of buildings with many potential implications for building energy use

Role of the U.S. Department of Energy

A leadership role for the US Department of Energy is to undertake aggressive research and technology transfer programs which: (1) help stimulate the paradigm shift toward excellent indoor environments, thereby improving the health and economic well-being of the US population and the competitiveness of US businesses; and 2) guide the US response so that energy-efficient technologies and practices are used whenever possible to provide excellent IEQ.

Such a role would be consistent with DOE's mission as an agency that seeks to benefit the U.S. public and U.S. businesses, in this case by developing a scientific foundation for improvements in health and productivity. This role would also be fully consistent with DOE's energy-efficiency mission. Many technologies and practices that reduce building energy use can also improve IEQ (IPMVP 1998, Fisk and Rosenfeld 1998, Fisk 2000b); thus, health and productivity gains could become a new stimulus for building energy efficiency. On the other hand, if DOE largely ignores this issue, building designers and operators may choose energy-inefficient methods of improving IEQ since the economic value of productivity gains will often outweigh the energy costs.

This role for DOE is also consistent with DOE's mission and history of advancing science and technology in the buildings' arena. In addition to a long-standing but modest-size program of research on building ventilation, IEQ, and health, DOE and its contractors have unique expertise and research capabilities related to whole-building performance, HVAC, building envelopes, and building control systems as well as established connections to buildings' industries and established programs for promoting improvements to buildings. The DOE expertise in buildings, unmatched by that in any other governmental or non-governmental organization, is essential for this area of research because improvements in IEQ that enhance health depend on changes to the design, operation, use, and maintenance of buildings.

DOE's activities in this field could also be a source of increased prosperity. There is a growing realization that science and technology have been a major source of prosperity in the US. Per unit of investment, a research and technology program explicitly focused on IEQ, health, and productivity should be particularly effective in enhancing prosperity,

Coordination with Other Agencies

An expanded research and technology transfer program in this area by DOE would need to be coordinated with other governmental and private sector programs. In the federal sector, EPA has IEQ programs, with a greater focus on IEQ education and policy than on research, and NIOSH has a modest program, primarily focusing on the relationship of the non-industrial work environment with asthma. Additionally, NIH supports a much larger program of relevant research, primarily basic health research on asthma, allergy, infectious disease (but not the influence of buildings on infectious), and toxic effects of metals and pesticides, typically without a strong contribution from the field of building science. There are minimal overlaps between the programs of different federal agencies. While all these agencies have an important role, their programs on IEQ are modest and focused, and do not obviate the need for the DOE role with a much larger focus on the building science and energy aspects of IEQ and their relationship to health and productivity.

Nature of Knowledge Gaps

A recent review by the US General Accounting Office (GAO 1999) identified the broad categories of IAQ-related knowledge gaps:

1. The identity and sources of pollutants;
2. Mechanisms by which people are exposed to them;
3. The health effects resulting from prolonged and intermittent exposures to low-level concentrations of chemical and biological pollutants as well as complex pollutant mixtures;
4. The most cost-effective strategies for reducing pollutant sources, exposures, and consequent health effects.

The GAO review stresses the importance of multidisciplinary research approaches to this research.

Research and Technology Transfer Needs of Particular Relevance for DOE

Many features of building design, operation, and maintenance affect both occupant health/productivity and building energy consumption. An expanded DOE research and technology transfer program on the interrelationships among buildings, health, productivity, and energy could focus most explicitly on these building design, operation and maintenance features. In some instances, the health benefits may be adequately documented and DOE-supported work could emphasize technology development and demonstration. In other instances, DOE is already supporting technology development or energy-performance assessment, but additional work is necessary to quantify and demonstrate the health benefits. The subsequent paragraphs describe these more specific research and technology transfer needs. Considerable but not exclusive emphasis has been placed on "win-win" opportunities for research and technology transfer that could improve health and simultaneously save energy.

Building Ventilation

The evidence that increased rates of outside air ventilation generally lead to improvements in perceived air quality, satisfaction with air quality, and health is becoming very persuasive (Seppanen et al. 1999). Consequently, a shift toward higher ventilation rates or more effective methods of controlling pollutant exposures with ventilation seems inevitable. In general, higher ventilation rates will increase building energy use and peak energy demands. [In U.S. residential and service-sector buildings, an estimated 25% of energy use is for ventilation (Orme 1998)]. However, DOE could help to shape the response to the emerging information so that increased energy consumption and peak demands are minimized. In addition, DOE can help to develop and promote use of some HVAC technologies that simultaneously increase ventilation rates (or ventilation efficiencies) and save energy. The following ventilation-related topics should be of particular interest to DOE:

Minimum Ventilation Requirements

Existing data on the relationship of ventilation rates with health outcomes are predominately from studies in moderate to large office buildings located in temperate or cool climates (Seppanen et al. 1999) and most of these studies have employed ventilation rates less than 10 L s-1 per person. There remain very strong needs for studies: of the potential benefits of increasing ventilation rates above 10 L s-1 per person; of ventilation requirements in humid climates; and of ventilation requirements in other types of buildings such as small offices, schools, retail buildings, and dwellings. In addition, since there appears to be no threshold ventilation rate above which health outcomes do not improve (Seppanen et al. 1999), future research needs to quantify the dose-response relationships between ventilation rates and health outcomes so that the magnitude of health benefits can be weighed against incremental energy and equipment costs.

Better Measurement And Control of Ventilation Rates

In U.S. residences, rates of ventilation depend on the quantity of accidental cracks and holes in building envelopes and ducts, on weather conditions, and on window and exhaust fan use. Even in mechanically-ventilated commercial buildings, HVAC systems very rarely include integral systems for measuring and controlling minimum rates of outside air supply; thus, ventilation rates are poorly controlled. The minimum ventilation rates measured in surveys of such buildings often differ substantially from the minimum ventilation rates specified in the applicable codes (Seppanen et al. 1999, Fisk et al. 1992, Lagus Applied Technologies 1995, Teijonsalo et al. 1996, Turk et al. 1989). While the problems associated with measurement and control of outside air ventilation rates have been recognized for many years, there has been little progress toward overcoming the problems. The large range of ventilation rates among buildings suggests an opportunity to improve health and satisfaction with air quality by increasing ventilation rates in buildings with low ventilation rates and decreasing ventilation rates in buildings with high ventilation rates. Due to the dose-response relationships between ventilation rates and health outcomes (Seppanen et al. 1999), the average level of health symptoms and satisfaction with air quality might be improved without increasing the total ventilation rate of the building stock or increasing the associated energy use. Consequently, research and technology transfer in needed on energy-efficient means of measuring and controlling building ventilation rates.

Heat Recovery from Ventilation Air

Heat recovery systems that transfer heat (and sometimes moisture) between ventilation exhaust airstreams and the incoming outside air can diminish the energy required for ventilation. These systems are used commonly in northern Europe but rarely in the regions of the US with similar climates. Increasing ventilation rates will make heat recovery more cost effective. The technologies required for heat recovery from exhaust ventilation air are already available, but there is a need for demonstrations and guidelines on how and when to properly implement and operate these systems. By quantifying and demonstrating the benefits and costs of increased ventilation with heat recovery DOE can stimulate the market for these strategies.

Displacement Ventilation

A ventilation technology used commonly in Europe, but very rarely in the U.S., is displacement ventilation. This technology supplies air near the floor and produces an upward airflow pattern that is more effective in limiting pollutant exposures than an equivalent amount of well-mixed ventilation. Relative to conventional mixing ventilation, displacement ventilation also removes warm air more effectively. Displacement systems usually supply 100% outside air, increasing ventilation rates relative to conventional systems that supply predominately recirculated air; consequently, heat-recovery systems are often combined with displacement ventilation for energy efficiency. Increased use of displacement ventilation, where appropriate, could reduce health effects and, in some cases, save energy. Research and technology transfer is needed to identify and demonstrate the best opportunities for displacement ventilation.

Task Ventilation

Breathing rates are about 0.1 L s-1 per person, only 1% of the rate of the rate of outside air supply to buildings (Fanger 2000). Task ventilation (sometimes called personal ventilation) systems that supply outside air preferentially to the breathing zone may be able to substantially reduce pollutant exposures and improve health while maintaining or even reducing quantities of outside air. These systems supply air near each occupant's breathing zone. Moderate, 20% to 50%, exposure reductions have been demonstrated for some commercially-available air supply technologies (Faulkner et al. 1993,1998); however, optimization of the ventilation performance of these systems should bring even larger reductions in exposure.

Evaporative Cooling

In some climates, direct or indirect evaporative cooling systems can replace compressor-based cooling. These evaporative systems often supply 100% outside air; consequently, they increase ventilation rates and will reduce indoor concentrations of many indoor-generated pollutants. Energy savings relative to compressor-based cooling can be large (e.g., 50%). Research and technology transfer is needed to develop and optimize systems, quantify and demonstrate IAQ and energy performance gains, and evaluate and address concerns about maintenance and increased indoor humidities.

Moisture and Humidity Problems

Figure 3 illustrates the strong relationship of adverse respiratory and asthma symptoms with moisture problems or the mold contamination commonly associated with moisture problems. Many of these moisture problems are a consequence of water leaks in building envelopes, particularly roofs. Other moisture problems result from condensation of water vapor in walls or from inadequate humidity control by HVAC systems in humid climates. The extent of mold contamination resulting from a moisture problem appears to depend on the selection of building materials. In addition to adversely affecting health, moisture problems degrade the thermal performance of building envelopes, increase energy use, and cause extensive materials damage requiring costly repairs. The prevalence and severity of moisture problems are not fully understood, but a very significant number of buildings are affected. For example, in the U.S. Census data about 15% of houses report water leakage from outdoors (Committee on the Assessment of Asthma and Indoor Air 2000). DOE has a broad range of relevant expertise on building envelope performance (including roofs and foundations), on air and moisture transport through envelopes, and on HVAC performance. Expanded DOE research and technology transfer in this field could help to improve health of the U.S. population, save energy, and prevent costly damage to U.S. buildings.

Higher indoor humidities are associated with increased levels of house dust mites (Chapter 8, Committee on the Assessment of Asthma and Indoor Air 2000). The allergens from dust mites, arguably the most important of allergens for humans, are associated with both the development and exacerbation of asthma (Chapter 5, Committee on the Assessment of Asthma and Indoor Air 2000). Particularly elevated indoor humidities, e.g., above 80% RH, can also facilitate growth of molds indoors; however, the influence of more moderate humidities on indoor mold growth is uncertain (Chapter 8, Committee on the Assessment of Asthma and Indoor Air 2000). Again, there is a link to energy -- maintaining low humidities during air conditioning increases energy use. Many associated research questions remain. The relationships of humidity to dust mite and mold contamination are still inadequately understood. Additionally, research, technology development, and technology transfer efforts are needed to improve humidity control by HVAC systems.

Efficient Air Filtration

Air filtration (or other particle air cleaning systems) show some promise in moderately reducing allergy and asthma symptoms (Chapter 10, Committee on the Assessment of Asthma and Indoor Air 1999) and portable air cleaners are commonly used by allergic and asthmatic individuals. In addition, more efficient air filtration systems in HVAC systems can dramatically reduce indoor concentrations of fine particles from outdoors (Fisk et al. 2000c). There is persuasive evidence that death rates, hospital admissions, and respiratory symptoms increase with higher outdoor particle concentrations (EPA 1996). Since people are indoors 90% of the time, the exposures to these outdoor particles occur predominately indoors. Consequently, one would expect that the adverse health effects associated with outdoor particles could be substantially reduced through the use of more efficient filtration systems; however, these benefits have not been demonstrated. Once again, there are strong ties with building energy use. A 200 W portable air cleaner, operated continuously, would consume $170 of electricity per year. More efficient filters in HVAC systems also tend to increase fan energy requirements unless the filter is designed for a low airflow resistance. Research is needed to determine when particle air cleaning is (or is not) effective in improving health and to evaluate and demonstrate energy and cost effective efficient methods of particle air cleaning.

Better Indoor Temperature Control

Despite the significant attention placed on thermal comfort by building professionals, dissatisfaction with indoor thermal conditions is the most common source of occupant complaints in office buildings (Federspiel 1998). In a large field study (Schiller et al. 1988), less than 25% of the subjects were moderately satisfied or very satisfied with air temperature. Also, 22% of the measured thermal conditions in the winter, and almost 50% of measured thermal conditions in the summer, were outside of the boundaries of the 1988 version of the ASHRAE thermal comfort zone. Temperatures are also linked to health. In several studies, increased air temperatures are associated with increases in SBS symptoms (Mendell 1993, Mendell et al. 1999) and with reduced satisfaction with indoor air quality (Fang et al. 1998a, 1998b). These findings indicate that greater effort should be placed on HVAC system designs or controls that do a better job than current systems of maintaining thermal conditions within the prescribed comfort zones. Because indoor air temperatures influence occupant health symptoms as well as comfort, the recommended range of indoor temperatures may also need to be reexamined.

HVAC System Maintenance and Operation

Improved maintenance and operation of HVAC systems is another practice with the potential to simultaneously save energy and improve IEQ and health. As discussed above, Sieber et al. (1996) found that large increases in SBS symptom prevalences were associated with evidence of poorer ventilation system maintenance or cleanliness. Many common problems with HVAC system performance (some discussed previously) are reported anecdotally and in published literature. Examples of these problems include: fouling of cooling coils and drain pans by deposited particles and microbial growth; large indoor air temperature oscillations or temperatures maintained outside of the thermal comfort envelope; dirty duct systems; deterioration of HVAC insulation; missing air filters; poor control of indoor-outdoor or inter-room air pressure differences; closed fire dampers; poor air distribution leading to excessive noise, drafts, and thermal comfort problems; insufficient or excessive outside air ventilation; improper damper operation (sometimes the damper linkage is disconnected from the dampers or actuators); fans running backwards, not operating or operating at the wrong times; sensors that are far out of calibration or disconnected; and water leaks. Each of these problems may be due substantially to maintenance and operation problems, although design and construction limitations and errors also play an important role. Research and technology transfer programs are needed to determine the prevalence and underlying causes of these problems and to quantify and demonstrate the energy and IEQ benefits of problem prevention and remediation.

Rethinking HVAC Architectures

Many of the HVAC system problems (mentioned in the previous text) which increase energy use and deteriorate IEQ, have been recognized for many years; however, progress in resolving these problems has been very limited. Improvements to HVAC technologies tend to be incremental and to occur slowly. In parallel with efforts to incrementally-improve existing HVAC architectures, DOE, working in partnership with industry, could rethink HVAC from the ground up with simultaneous goals of improved IEQ, energy efficiency, and maintainability. Innovative HVAC architectures might include many of the following features: outside air supply separated from the system used for thermal conditioning; water used to transport energy around the building (pumping water is more energy- and space-efficient than blowing air through long ducts); individual control of thermal comfort at each workstation; outside air supply near the breathing zone of each workstation with airflow controlled by occupancy sensors; high efficiency particle filters; a modular design with easily removable and replaceable components so that maintenance occurs in the shop; and advanced sensors and controls. The initial step in this program would be to assemble a highly multidisciplinary panel of experts who will define objectives and work together on innovate HVAC architectures, unfettered by current product designs.

Natural Ventilation

Numerous cross-sectional studies have compared the prevalence of SBS health symptoms experienced in air-conditioned buildings with the prevalence experienced in naturally-ventilated buildings. A large majority of these studies have found that the occupants of the air-conditioned buildings report significantly more symptoms after controlling for other factors (Seppanen and Fisk 2000). The reason for these rather consistent findings is not known. One of the hypothesized explanations is that HVAC systems are sometimes contaminated, for example with microorganisms, deposited particles, and residual oils from the manufacturing process, and become a source of indoor air pollutants. These findings suggest that health symptoms might be reduced through increased use of natural ventilation within commercial buildings located in suitable climates. Naturally-ventilated buildings also tend to use less energy, consequently, simultaneous energy savings and improvements in health may be possible. However, additional research is needed before promoting a shift toward natural ventilation. Within the U.S., there has been only one modest-size study that compared symptom prevalences between naturally-ventilated and air-conditioned buildings (Mendell et al. 1996). Also, until the cause of the increased symptoms in naturally-ventilated buildings is known, it is premature to conclude that symptom prevalences will be lower in new naturally-ventilated buildings.

Indoor Pollutant Source Reduction

The most effective method of controlling the indoor concentrations of many indoor-generated air pollutants is to eliminate or reduce the sources present indoors. Many of these sources depend on the design, furnishing, operation, and maintenance of the building; for example, the selection of building and HVAC materials and office equipment. Building ventilation requirements are diminished when indoor pollutant source strengths are reduced; thus, indoor pollutant source reduction can save energy. Research and technology transfer efforts are needed to identify the sources that do and do-not affect health and to develop and demonstrate methods of eliminating or reducing the important sources.

Conclusions

1. There is relatively strong evidence that characteristics of buildings and indoor environments significantly influence the occurrence of communicable respiratory illness, allergy and asthma symptoms, sick building symptoms, and worker productivity.
2. Theoretical and empirical evidence indicate that existing technologies and procedures can improve indoor environments in a manner that increases health and productivity. Estimates of the potential reductions in adverse health effects are provided in Table 1.
3. Existing data and knowledge allows only crude estimates of the magnitudes of productivity gains that may be obtained by providing better indoor environments in a manner that improves health; however, the projected gains are very large. For the U.S., the estimated potential annual savings plus productivity gains, in 1996 dollars, are approximately $20 billion to $50 billion, with a breakdown as indicated in Table 1.
4. Over the next two decades, the current goal of providing an adequate indoor environment may be replaced by an emphasis on providing excellent indoor environments that maximize the health, satisfaction, and performance of building occupants. Factors underlying such a paradigm shift would include increasing affluence of the U.S. population, increased expectations for excellent health, the desire to contain health care costs, and the rapidly increasing evidence, summarized in this paper, that IEQ affects health and productivity.

Table 1

Estimated Potential Productivity Gains from Improvements in Indoor Environments

Source of Productivity Gain	Potential Annual Health Benefits	Potential U.S. Annual Savings or Productivity Gain (1996 $ billion U.S.)
Reduced respiratory illness	16 to 37 million avoided cases of common cold or influenza	6–14
Reduced allergies and asthma	8% to 25% decrease in symptoms within 53 million allergy sufferers and 16 million asthmatics	1–4
Reduced sick building syndrome symptoms	20% to 50% reduction in SBS health symptoms experienced frequently at work by ~15 million workers	10–30

5. A leadership role for the U.S. Department of Energy is to undertake aggressive research and technology transfer programs which: (1) help stimulate the shift towards excellent indoor environments, thereby improving the health and economic well-being of the US population; and 2) guide the U.S. response so that energy-efficient technologies and practices are used whenever possible to provide excellent IEQ. Research and technology transfer topics that provide opportunities for simultaneous energy savings and improvements in health include the following: building ventilation; evaporative cooling; reducing moisture and humidity problems; efficient air filtration; better indoor temperature control; natural ventilation; HVAC system maintenance and operation; rethinking HVAC architectures; and indoor pollutant source control.

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