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Health and Productivity Benefits of Improved Indoor Air Quality

Chad B. Dorgan, P.E.
Member ASHRAE

Charles E. Dorgan, Ph.D., P.E.
Fellow ASHRAE

Marty S. Kanarek, Ph.D.

Alexander J. Willman, P.E.
Member ASHRAE

ABSTRACT

This paper is a summary of two studies completed for a national contractor's association on the health costs and productivity benefits of improved IAQ. The original study documented the general health costs and productivity benefits of improved IAQ. The second study expanded the scope to include medical cost reductions for specific illnesses from improved IAQ.

General information on the objectives, assumptions, definitions, and results of the studies are presented, followed by detailed information on research methodology, building inventory and wellness categories, health and medical effects of poor IAQ, health cost benefits, productivity benefits, recommended improvements, and conclusions and future improvements.

INTRODUCTION

Due to the large amount of time—up to 95% (ASHRAE 1993)—that the average individual spends indoors, the quality of the indoor environment has a significant effect on the health and productivity of employees. Indoor environmental quality (IEQ) is composed of factors such as space temperature, humidity, noise, lighting, interior design and layout, building envelope, and structural systems. A subset of IEQ is indoor air quality (IAQ). The factors that define IAQ are temperature, humidity, room air motion, and contaminants.

With poor IAQ, employees can suffer significant impairment of health and productivity. Productivity is a measure of the quality/quantity of accomplishments actually completed by an employee rather than what could be accomplished under ideal circumstances. Productivity can be a measured value, such as sales, profits, the number of errors per hour, or actual time at work. It can also be a subjective value, such as a personal evaluation, benchmarked satisfaction of either employees or customers, or supervisors' annual evaluations.

In this study, commercial buildings included all building stock that was not either industrial or residential, as defined in Energy Information Agency (EIA) reports. This includes government and institutional buildings, retail buildings, offices, schools, hospitals, and other nonindustrial buildings.

IAQ is only one of the components that affect productivity in commercial buildings and organizations. Other factors, including management style, education, training, experience, salary, business stress, competition, and workload, must be accounted for in any productivity benchmarking study to obtain valid results.

This paper is a summary of two studies completed for a national contractor's association on the health costs and productivity benefits of improved IAQ. The original study (Dorgan Associates 1993) documented the general health costs and productivity benefits of improved IAQ. The second study (Dorgan et al. 1995) expanded the scope to include medical cost reductions for specific illnesses.

General information on the objectives, assumptions, definitions, and results of the studies are presented, followed by detailed information on research methodology, building inventory and wellness categories, health and medical effects of poor IAQ, health cost benefits, productivity benefits, recommended improvements, and conclusions and future improvements.

Objectives

The studies were conducted with the following objectives:

- Develop a classification system for IAQ problems in commercial buildings in the United States.
- Quantify the health cost benefits of good IAQ.
- Quantify the productivity benefits of good IAQ.
- Determine the cost to implement solutions for typical IAQ problems.
- Identify future research requirements.

Chad B. Dorgan is vice president, engineering, for Dorgan Associates, Inc., Madison, Wisc. **Charles E. Dorgan** is director of the HVAC&R Center and **Marty S. Kanarek** is an assistant professor at the University of Wisconsin, Madison. **Alexander J. Willman** is president of Quantum Technology, Inc., Springfield, Va.

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Assumptions

Due to the relative infancy of linking productivity to IAQ and the resulting lack of information in specific formats, several assumptions had to be made to obtain conservative results. These include:

- Building and employee distribution data from the Energy Information Agency (EIA) was accepted as accurate and representative as a whole.
- Values reported in other studies that did not provide detailed research procedures may have high benefit estimates. For this report, a conservative percentage of these values was used.
- Only the direct benefits of improving the IAQ were considered. Secondary benefits, such as fewer interoffice problems due to reduced stress caused by improved IAQ, are difficult to estimate and were not included.
- It was assumed that experienced professionals are involved in determining the proper renovations to be implemented, which, once installed, are properly maintained to avoid future IAQ problems (includes training of operation and maintenance personnel).

Results

The productivity and health benefits determined by the results in this study affect a large proportion of those who work, visit, do business, or are customers in commercial buildings in the United States. The benefits include monetary (profits or income), quality and (fewer low-level health issues), and satisfaction (reduced complaints). These results for direct employee health-related productivity benefits are summarized in Table 1. The total productivity benefits for commercial buildings are summarized in Table 2. Both quantifications are based on all buildings meeting ASHRAE Standards 62-1989 and 55-1992 and related IAQ standards.

The data in Table 2 are based on information gathered for, but not reported in the original reports (Dorgan Associates 1993; Dorgan et al. 1995) in that the client was only interested in employee health-related productivity and health benefits linked to IAQ in commercial buildings (nonindustrial).

Definitions

During the literature review for this project it became apparent that there were multiple definitions for almost every key term used in the IAQ field. Therefore, consistent definitions were developed based on published information from ASHRAE and the United States Environmental Protection Agency (EPA). Three of the key definitions are for IAQ, sick building syndrome (SBS), and building-related illness (BRI).

Indoor Air Quality (IAQ). ASHRAE *Terminology of HVAC&R* (ASHRAE 1991) defines indoor air quality as

> attributes of the respirable atmosphere (climate) inside a building including gaseous composition, humidity, temperature, and contaminants (ASHRAE 1991).

TABLE 1
Summary of Worker Productivity Benefits

Inventory	
• Number of commercial buildings in United States	4,149,000
• Total space	58.1 billion ft^2 (5.4 million m^2)
• Number of workers	68.9 million
Productivity and Health Benefits	
• Annual total productivity benefits	\$54.7 billion per year
• Annual reduced health cost	\$8 billion per year
• Annual total productivity and health benefits	\$62.7 billion per year
• Annual employee-related benefits, total	\$910/worker per year
	\$1.08/ft^2·yr (\$11.61/m^2·yr)
Cost to Implement	
• Implementation of all identified IAQ improvements	\$87.9 billion
• Average cost per area	\$1.51/ft^2 (\$16.28/m^2)
• Average cost per worker	\$1,276
• Initial average economic simple payback	1.4 years
• Annual cost to sustain all improvements	\$4.8 billion per year
Net 20-Year Present Value of Benefits Less Cost (I = 3%)	
• For all improvements	\$774 billion
• Per area for all improvements	\$13.31/ft^2 (\$143.33/m^2)
• Per worker for all improvements	\$11,227 per worker

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TABLE 2
Summary of Total Productivity Benefits

Productivity and Health Benefits	
• Annual total productivity benefits	\$54.7 billion per year
• Annual reduced health costs	\$8 billion per year
• Annual total productivity and health benefits	\$62.7 billion per year
• Including annual sales benefits	\$211.2 billion per year
• Annual employee-related benefits, total	\$3,065 per worker per year $\$3.64/ft^2 \cdot yr$ ($\$39.11/m^2 \cdot yr$)
Cost to Implement	
• Implementation of all identified IAQ improvements	\$120 billion
• Average cost per area	$\$2.07/ft^2$ ($\$22.22/m^2$)
• Average cost per worker	\$1,742
• Initial average economic simple payback	0.56 years
• Annual cost to sustain all improvements	\$6.6 billion per year
Net 20-Year Present Value of Benefits Less Cost (I = 3%)	
• For all improvements	\$2,924 billion
• Per square meter for all improvements	$\$50.33/ft^2$ ($\$541.48/m^2$)
• Per worker for all improvements	\$42,438 per worker

Air contaminants can be classified as "particulate or gaseous, organic or inorganic, visible or invisible, toxic or harmless, submicroscopic, microscopic, or macroscopic, stable or unstable" (ASHRAE 1993).

Sick Building Syndrome (SBS). The ASHRAE Position Paper on Indoor Air Quality (ASHRAE 1987) defines SBS as follows:

> The term "sick building" is used to describe a building in which a significant number (more than 20%) of building occupants report illness perceived as being building-related. This phenomenon, also known as "sick building syndrome," is characterized by a range of symptoms including, but not limited to, eye, nose, and throat irritation, dryness of mucous membranes and skin, nose bleeds, skin rash, mental fatigue, headache, cough, hoarseness, wheezing, nausea, and dizziness. Within a given building, there usually will be some commonality among the symptoms manifested as well as temporal association between occupancy in the building and appearance of symptoms.

Building-Related Illnesses (BRI). BRI is defined as a specific recognizable disease entity that can be clearly related to chemical, infectious, or allergic agents in buildings. The cause of the illness is determined by clinically lab testing patients and by identifying the source in the building. Hypersensitivity pneumonitis, humidifier fever, occupational asthma, and Legionella infection often are included as BRI. Indicators of BRI are (U.S. EPA 1991):

- Building occupants complain of symptoms such as cough, chest tightness, fever, chills, sinus congestion, headaches, and muscle aches.
- The symptoms can be clinically defined and have clearly identifiable causes.
- Complainants may require prolonged recovery times after leaving the building.

RESEARCH METHODOLOGY

The research methodology used for these studies focused on the compilation of previous research and reports, both published and unpublished, dealing with the link between IAQ and productivity. More than 500 reports were reviewed. These include published reports from both the U.S. and Europe, international proceedings, and personal correspondence. These are listed in the full reports (Dorgan 1993; Dorgan et al. 1995). From this review, the key reports were sorted and their data summarized. A description of the specific methodology used for individual topics is included below. These topics are:

- Wellness categories (baseline).
- Building and employee inventory.
- Health and medical effects.
- Health cost benefits.
- Productivity benefits.
- Recommended improvements.
- Other benefits.

Wellness Categories

Each report reviewed for building wellness classified commercial buildings differently. The majority of the reports used two general categories. Typically, this was "sick" or "healthy," but variations such as "buildings without known problems" and "problem buildings" (Woods 1989, 1991) did exist. Other categories of buildings found, include (Burge et al. 1987; Putnam et al. 1989; Robertson et al. 1985; Skov et al. 1989; Woods et al. 1987):

- Buildings with high and low rates of IAQ-related complaints.
- SBS buildings as a percentage of the total.
- Occupant response above and below a given level.

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- Healthy building characteristics.
- Number of SBS-type symptoms reported.
- Other combinations of methods of reporting the data.

In order to estimate the national implications of unsatisfactory and poor IAQ in terms of affected employees' health and productivity, a detailed classification of buildings in terms of wellness level was necessary. For this report, the various categories found in the different reports were compared and integrated to obtain consistent and definable categories. The results from each of the reports were then put into the new categories, and an average distribution of buildings by wellness category was determined.

Building and Employee (Worker) Inventory

Building categories based on building use were obtained from the U.S. Energy Information Administration, *Commercial Buildings Characteristics 1989* (DOE 1991). The number of buildings, amount of floor space, and the number of workers (employees or occupants) in each building category were obtained from this source. For a given building type, the number of employees allocated to each wellness category was based on the valid published reports.

Health and Medical Effects

The primary concern with unsatisfactory and poor IAQ is the impairment of the employees' health and related illnesses. Impairment of health not only affects the personality and happiness of an employee but also increases medical costs for employees and employers. A review of research articles from medical, engineering, and legal databases and from unpublished sources was conducted to evaluate the health and medical effects of unsatisfactory and poor IAQ. Three diseases were reviewed from an epidemiology viewpoint in the second study (Dorgan et al. 1995):

- hypersensitivity pneumonitis (HP),
- occupational asthma (OA),
- sick building syndrome (SBS).

Health Cost Benefits

From the results of the epidemiological investigations, health cost benefits were determined for acute respiratory disease (ARD), building-related illnesses (BRI), and mild IAQ and SBS symptom-related illnesses. The cost data were from several sources, including

- Brundage et al. (1998), Dixon (1985), and Woods (1989) for ARD;
- researchers' experience and judgment;
- conversations with operation and maintenance people on illness prevalence in buildings related to poor IAQ;
- conversations with medical researchers on clinic visits and hospitalizations related to poor IAQ.

Productivity

Published and unpublished research projects and reports dealing with productivity in relation to IAQ were reviewed. The definition of productivity and the methodology used in the reports were clearly analyzed to ensure that only conservative values of productivity were used in this study. The results of these previous studies and reports were combined with the researchers' experience to determine the percentage productivity increase for each building wellness category. With the number of workers in each wellness category and the annual salary and fringe benefits of the workers known, the total productivity cost benefits achievable by upgrading a specific wellness category building to a healthy level was computed.

Recommended Improvements

Recommended improvements were developed from the researchers' experience on remediation of IAQ problems in commercial buildings. The ultimate goal of implementing the improvements was that all commercial buildings in the United States met or exceeded *ANSI/ASHRAE Standard 62-1989, Ventilation for Acceptable Indoor Air Quality*, and *ANSI/ASHRAE Standard 55-1992, Thermal Environmental Conditions for Human Occupancy* (ASHRAE 1989, 1992).

Other Benefits

During the course of the study, other non-health/productivity benefits were identified. These included benefits to individuals, businesses, and communities and avoidance of litigation. The benefits for individuals, businesses, and communities are due to jobs generated to implement the IAQ improvement projects and were estimated using average wage rates and the cost of improvements.

Avoidance of litigation was a major benefit, often overlooked. While there are no guarantees, case studies were developed showing what happens when the IAQ degrades. This can be viewed as a risk management economic benefit in that it is involved on a percentage of all buildings.

RESULTS OF RESEARCH

Using the research methodology described above, results were obtained for

- building wellness categories,
- building inventory,
- health and medical effects of poor IAQ,
- health cost benefits,
- productivity benefits,
- recommended improvements.

Building Wellness Categories

Five building wellness categories were developed in order to fully classify the existing commercial building stock in the United States. These are

- healthy;
- generally healthy;
- unhealthy, source unknown;
- unhealthy, source known;
- SBS/BRI.

The rational for selecting these five categories was based on how other publications reported information on buildings. Although, a number of publications use "sick," "problem building," "satisfactory," and other terms, as well as "healthy" and "unhealthy"; it was determined that the above categories reflected the most positive terminology. It further reflected the health relationship of productivity that is related to IAQ.

For each category, characteristics were developed in order to clearly define what was right and what was wrong with a facility and to make it easier to determine how to improve IAQ in unhealthy buildings.

1. Healthy

- Always meets ASHRAE Standards 62-1989 and 55-1992 during occupied periods.
- Eighty percent or more of the occupants do not express dissatisfaction with the indoor air quality.
- Building systems are well maintained.
- Building health management exists.

2. Generally Healthy

- Meets ASHRAE Standards 62-1989 and 55-1992 during most occupied periods.
- The factors leading to indoor conditions that do not comply with the ASHRAE standards for some of the occupied hours are:
  —Relative humidity falls below recommended minimum 30% in winter.
  —Relative humidity temporarily rises above recommended maximum 60% during summer days.
  —Outdoor air ventilation rate temporarily drops below recommended minimum due to occupant density being greater than design value.
  —Lack of maintenance leads to periodic IAQ degradation.
  —The HVAC system does not operate during low occupancy.

3. Unhealthy, Source Unknown

- Would fail to meet ASHRAE Standards 62-1989 and 55-1992 during most occupied periods, if evaluated.
- More than 20% of the building occupants would consistently express dissatisfaction with the indoor air quality.
- Less than 20% of the occupants would complain of SBS symptoms.
- Components of HVAC systems and controls that are sources of IAQ problems have not been identified by the building management or operating staff.
- SBS symptoms and illnesses shown by occupants would not be related specifically to the building, if evaluated.
- Investigations or surveys reported the building had the above unhealthy characteristics, but the building owners or operators did not recognize that a problem existed.

4. Unhealthy, Source Known

- Fails to meet ASHRAE Standards 62-1989 and 55-1992 during most occupied periods.
- More than 20% of the building occupants consistently express dissatisfaction with the indoor air.
- Less than 20% of the occupants show SBS symptoms.
- Subsystems causing poor IAQ have been identified; however, the source of the IAQ and SBS problems cannot be linked to a specific HVAC component.
- Occasional high levels of IAQ-related complaints or symptoms.

5. SBS/BRI

- More than 20% of the building occupants complain of SBS symptoms.
- One or more cases of BRI have been documented.
- Occupants report daily symptoms of IAQ-related illness while in the building.

Building and Worker Inventory

The distribution of specific building types by wellness category is given in Table 3.

The specific sources for Table 3 include (Woods 1989):

- Woods — 50% to 70% of nonindustrial buildings in the U.S. are healthy buildings. (This also includes generally healthy buildings.)
- Burge — 9% SBS/BRI buildings.
- Putnam — 20% SBS/BRI and unhealthy buildings, source known.
- Robertson—15% to 30% SBS/BRI and unhealthy buildings, source known.
- Woods — 20% to 30% SBS/BRI and unhealthy buildings, source known

Therefore, 60% of all commercial building types were considered to be healthy or generally healthy, 10% each for SBS/BRI and unhealthy buildings, source known, and 20% for unhealthy buildings, source unknown. The rationale for distribution of office buildings and education, mercantile and service, lodging, and food service buildings was primarily researchers' experience and judgment and other reports.

The building inventory data for a selective number of the building categories are given in Table 4. Data for the remain-

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TABLE 3
Distribution of Specific Building Types by Wellness Categories,%

Building Wellness Category	National Building Wellness	Office Buildings		Education	Mercantile and Service	Lodging [1] (Humid Climate)	Food Service
		Gov't.	Others				
Healthy	20	10	30	10	30	12	15
Generally Healthy	40	20	40	20	35	18	35
Unhealthy, Source Unknown	20	35	15	35	20	40	30
Unhealthy, Source Known	10	20	10	20	10	15	12
SBS/BRI	10	15	5	15	5	15	8

1. Humidity is a problem in all lodging buildings. Humid climates typically worsen the IAQ problems.

TABLE 4
Building Inventory Data

Building Category	Total Number of Buildings, Thousands	Total Floor Space, ft (m), Millions [1]	Number of Workers (Thousands)					
			Healthy	Generally Healthy	Unhealthy, Source Unknown	Unhealthy, Source Known	SBS/BRI	Total [2]
Food Service	241	1,167 (108)	291	680	583	233	155	1,942
Health Care	80	2,054 (191)	845	1,690	845	423	423	4,226
Mercantile and Service	1,278	12,365 (1149)	3,724	4,345	2,483	1,241	621	12,414
Office [3]	679	11,802 (1096)	7,223	10,001	5,278	3,334	1,945	27,718
All Other	1,871	30,652	3,679	7,280	5,834	3,034	2,673	22,500
Total Used	4,149	58,040	15,762	23,996	15,023	8,265	5,817	68,863

1. U.S. Energy Information Administration, *Commercial Buildings Energy Consumption Survey: Commercial Buildings Characteristics 1989*, Table 28.
2. U.S. Energy Information Administration, *Commercial Buildings Energy Consumption Survey: Commercial Buildings Characteristics 1989*, Table 19.
3. The "All Other" building category includes assembly, education, food dales, public order and safety, skilled nursing, wareh use, and other (hangar, crematorium, public restrooms/showers, and telephone exchange).

ing building sectors are included in the full report (Dorgan et al. 1995).

Health and Medical Effects of Poor IAQ

The results of an epidemiological review of the available research articles on health and medical effects are summarized below:

Hypersensitivity Pneumonitis (HP). Although most studies did not specifically investigate the effect of IAQ on the outbreaks of respiratory diseases, it was determined that hypersensitivity pneumonitis in office buildings usually is associated with the microbial contamination of ventilation air of HVAC systems. Culprits identified included open cold-water-spray humidification and cooling systems.

Occupational Asthma (OA). No statistically significant evidence was found to relate the number of asthma cases to indoor air quality in office building environments. While a prevalence of asthma was found apparently to be related to the poor indoor air environment in the office building, the sampling size made the study inconclusive (Hoffman et al. 1993).

Sick Building Syndrome (SBS). Based on the research results analyzed, it is certain that SBS is linked to IAQ problems related to HVAC systems. Sufficient data show a link between SBS symptoms and the indoor air quality in a building. The support of this conclusion was a statistically significant odds ratio. An odds ratio is the ratio of the risk of disease in exposed individuals to the risk of the disease in unexposed individuals.

The odds ratios obtained by Jaakkola and Miettinen (1995) can be used to measure the strength of association between exposures (mechanical ventilation and natural ventilation) for SBS symptoms. Their odds ratios ranged from 1.31 to 2.32 for SBS symptoms. This means that the individuals exposed to a mechanically ventilated system are 1.31 to 2.32 times more likely to develop SBS symptoms than those exposed to a naturally ventilated system. All of the OR values cited in the Jaakkola and Miettinen study were statistically significantly larger than 1.0. This also is true of the adjusted

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relative risk, 1.51, obtained by Brundage et al. (1988) (U.S. EPA 1991) for acute respiratory diseases (ARD). The ARD incidence rate obtained by Brundage et al. in mechanically ventilated army barracks was 0.67 per 100 trainee-weeks, compared to 0.46 per 100 trainee-weeks in old barracks with natural ventilation.

Odds ratios do not need to be significantly greater or less than 1.0 to show a causal relationship between the disease of interest and the exposure if a significant general population is exposed to the disease. Odds ratios derived from epidemiological studies in many areas, such as formaldehyde, are often low. However, the impact of low odd ratios on the public health is immense due to the large population that is affected. Therefore, for IAQ where at least 10% of the general population is exposed to SBS symptoms, the impact is significant enough to warrant action.

Some of the best evidence of the impact of IAQ is the comparison of mechanically ventilated buildings to naturally ventilated buildings. Within these studies, the best mechanically conditioned buildings did perform better than naturally ventilated buildings. Since humidity is an issue in most U.S. buildings and new buildings are constructed to be energy efficient, almost all U.S. construction can only achieve adequate indoor air quality with a mechanical system. A review of existing epidemiological studies indicates a strong need for adequate mechanical systems in buildings to achieve acceptable IAQ. This is required to prevent impairment of occupant health and to provide a controlled environment that will increase functional productivity.

Health Cost Benefits

Health cost benefits were determined for ARD, miscellaneous diseases, and SBS problems. The total benefits to health costs due to improving the IAQ were estimated to be $8 billion per year.

ARD-Related Health Cost Reduction. The ARD cost reduction was calculated using three separate methods in order to obtain a more accurate estimate. The average medical cost benefit related to ARD as a result of improving the IAQ in commercial buildings was estimated to be $1.2 billion per year.

Other BRI-Related Cost Reduction. The incidence rate for all other miscellaneous diseases, which include humidifier fever, Legionnaires' disease, occupational asthma, and lower respiratory diseases from mold and bacteria, will likely be greater than that for only ARD. However, to maintain a conservative approach, the research team estimated that the incidence rate was two-thirds of the ARD rate. Therefore, the health costs attributable to the combination of these other illnesses were estimated to be $800 million per year.

Mild IAQ-Related Cost Reduction. There are health costs associated with general IAQ illnesses, including SBS symptoms of rashes, eye irritation, nausea, headaches, and mild coughs. There were no statistically reliable data available on the frequency of hospitalizations and clinic visits due to these illnesses. However, based on a review of buildings over a 20-year period and on conversations with operation and maintenance personnel and with medical researchers, the medical costs due to mild IAQ-related hospitalizations and clinic visits were estimated to be $6.0 billion per year.

Productivity Benefits

Research studies document a productivity loss of 2% to 100% in SBS buildings. The 100% loss results from the complete shutdown of a 22-story office building in greater Washington, D.C., while the experts tried to identify the indoor air pollutants (Hansen 1991). A majority of the studies indicate an average productivity loss of 10% due to poor IAQ. Therefore, by improving the IAQ, a conservative benefit of 6% could readily be achieved. The percentage increase in productivity for the remaining building wellness categories is as follows:

- Unhealthy, problem known 3.5%.
- Unhealthy, problem unknown 3.5%.
- Generally healthy 1.5%.

The annual productivity benefits that can be obtained by upgrading the buildings of various wellness categories to a healthy level were determined for each building type. The total annual and per worker productivity benefits related to workers only in commercial buildings are presented in Table 5. This is the information that was used to develop the summary data in Table 1. Additional data were developed for cost and benefits per square foot (square meters) and were reported in Table 1. Table 2 includes the additional productivity benefits related to the economics of doing business. This includes profits, increased business, economic benefits to society (such as better education, more use of museums, faster recovery in hospitals, satisfaction with government, etc.). Buildings with floor space less than 10,000 ft were considered small buildings. Buildings with floor space between 10,000 ft^2 and 25,000 ft were considered medium buildings and with floor space greater than 25,000 ft , large buildings.

Recommended Improvements

A description and cost for the recommended improvements are detailed in the following sections.

Description of Recommended Improvements. The recommended measures required to improve the HVAC systems of existing buildings with poor IAQ are listed under two categories:

- Meet or exceed the requirements of *ASHRAE Standard 62-1989*.
  - —change the rate of outdoor air per person to 15 cfm or more
  - —monitor outdoor air quantity to meet ventilation requirements
  - —install local exhaust
  - —increase ventilation effectiveness
  - —maximize economizer cycle
  - —relocate air vents
  - —change the air filtration method
  - —reduce unwanted infiltration and/or exfiltration

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TABLE 5
Annual Productivity Benefits

Building Type	Wellness Category	Total Number of Workers		Productivity Increase Per Worker ($)		Benefits ($Millions)		
		Small	Med/ Large	Small	Med/ Large	Small	Med/ Large	Total
Totals	1. Healthy	3,896	12,059	$0	$0	$0	$0	$0
	2. Generally Healthy	5,871	18,174	435	435	3,048	9,434	12,482
	3. Unhealthy, Problem Unknown	3,679	11,390	1,016	1,016	4,596	14,228	18,824
	4. Unhealthy, Problem Known	2,036	6,304	1,016	1,016	2,613	8,089	10,702
	5. SBS/BRI	1,413	4,374	1,742	1,742	3,117	9,647	12,764
	Total	16,895	52,300	$4,209	$4,209	$13,373	$41,398	$54,772

- Improve space control to meet the health needs of Standard 62-1989 and meet or exceed the generally accepted requirements of Standard 55-1992.
    —improve space temperature control
    —improve control or provide positive control of humidity (dehumidification)
    —install humidification, self-contained steam humidifiers

Costs to Implement IAQ Improvements. The estimated cost of implementing each improvement in a building was estimated as a fraction of the new construction cost of a mechanical system for the building. The labor and material costs per building area were obtained. This number was then multiplied by the area inventory of the building category and the percent of buildings affected by each recommended HVAC measure to yield the cost of improvement. Costs were computed for five climatic zones of the United States. The total costs of improvements for small and medium/large buildings were estimated to be $7.6 billion and $80.4 billion, respectively. The grand total one-time cost was $87.9 billion.

Maintenance Program. Some of the improvements identified required an increase in the preventive maintenance program. This included recordkeeping of occupant complaints and training of maintenance and operation personnel. The cost for this increased maintenance was $4.8 billion per year.

CONCLUSIONS AND FUTURE RESEARCH REQUIREMENTS

A number of nonindustrial buildings in the U.S. stock have degraded indoor air quality. The percentage of buildings in each of the five levels of IAQ degradation (i.e., wellness categories) were determined based on previous research findings, researchers' experience and expert judgment, and conversations with operation and maintenance personnel and with medical personnel. A one-time upgrade cost of $87.9 billion, an annual operating cost of $4.8 billion, and a total annual benefit of $62.7 billion resulting in a simple payback period of 1.4 years was estimated as the productivity and health benefits for employees in all commercial (nonindustrial) buildings. This also results in a net 20-year present value of $774 billion ($13.31 per ft or $11,227 per worker). The productivity benefits related to IAQ are an employee health issue. The gains are related to a healthier indoor environment and healthier employees.

Therefore, to ensure the future competitiveness of the United States and of an international leader, the investment in IAQ must be made today to reap the productivity benefits documented in this paper. Further, all new and major system modifications must have IAQ as a priority design intent requirement.

In order to achieve this goal, further research is required:

- Research studies to fully investigate the causal relationship between hypersensitive pneumonitis (HP) and occupational asthma (OA) and the indoor air quality of commercial buildings.
- A set of guidelines to properly perform productivity studies and benchmark existing buildings.
- Case studies to determine the actual health and productivity benefits that result from improved indoor air quality due to the implementation of HVAC improvement measures.

Although the evidence is strong for relating health and economic benefits, many require further scientific data. This issue is following the same historic development as the debate on health issues and smoking/STS. The evident health and economic benefits are significant and need to be acted on now.

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