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Human Comfort and IAQ

A discussion of human comfort as the forgotten issue in the design of buildings

By the time you have read this article, you may be tired, irritable, and literally sick. The cause could well be the environment around you and, hopefully, not the article itself. Part of this cause is the outcome of energy conservation measures resulting from the energy crisis of the early 1970s. This resulted in tighter buildings, well caulked and sealed with membrane closures, lower lighting levels, reduced heating/cooling loads, lower ventilation rates, variable air volume systems, minimum outside air ventilation, etc. Part of it may be due to the extensive use of synthetic materials and their resultant emission of contaminants. However, an even larger reason is that, as an industry, we have not done our job. HVAC systems are generally inadequate, are just poorly designed, and are certainly seldom properly maintained. We have forgotten or neglected the most fundamental of all issues in building design—human comfort.

Our concerns for comfort in the 1960s and 70s were primarily measured in terms of temperature, humidity, and air change rates. On stringent programs (mostly institu-

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Table 1—Involved organizations and key publications.

National Institutes of Standards and Technology (NIST)
• Standard regulations and other technical criteria related to indoor air quality.
• Frequency and Distribution of Air Change Rates in Buildings
National Institute of Occupational Safety and Health (NIOSH)
• Manual of Analytical Methods
American Conference of Governmental Industrial Hygienist (ACGIH)
• Threshold Limit Values and Biological Exposure Indices
• A Manual of Recommended Practice for Industrial Ventilation, 1989
National Research Council (NRC)
• Commission on Engineering and Technical Systems—Policies and Procedures for Control of Indoor Air Quality
• Environmental Tobacco Smoke—Measuring Exposures and Assessing Health Effects
World Health Organization (WHO)
• Indoor Air Quality Research
• Air Quality Guidelines—Indoor Air Pollutants
• Indoor Air Pollutants—Exposures and Health Effects
Environmental Protection Agency (EPA)
• National Primary and Secondary Ambient Air Quality Standards
• Radon Reduction Methods—A Homeowner's Guide
• Exposure to Radon Daughters in Dwellings (NRPB)
• A Citizen's Guide to Radon
United States Academy of Science (UASA)
• *Guides for Short-Term Exposure of the Public to Air Pollutants*
Internatonal Standards Organization (ISO)
• International Thermal Comfort Standards (7730)
American Society of Heating, Refrigeration and Air-Conditioning Engineering (ASHRAE)
• Standard 62-76—Method of Testing Air Cleaning Devices
• Standard 55-1981—Thermal Environmental Conditions for Human Occupancy
• Standard 62-89—Ventilation for Acceptable Indoor Air Quality
• Standard 90A-80—Energy Conservation in New Building Design
• Position Paper—Indoor Air Quality, August 1987
• Position Statement—Indoor Air Quality, July 1982
Occupational Health and Safety Administration (OSHA)
• Air Contaminants—Permissible Exposure Limits
Air-Conditioning and Refrigeration Institute (ARI)
• Briefing Paper on Indoor Air Quality
U.S. Dept. of Health and Human Services (USDHHA)
• The Consequences of Involuntary Smoking
Electrical Power and Research Institute (EPRI)
• Manual on Indoor Air Quality, EPRI.FM-3469

tional), we might have thought about mean effective radiant temperature, looking at the effects of occupant clothing and the impact of cold radiant wall and glass surfaces. We may also have looked at terminal air velocities and minimum outside air per person.

Comfort today is also measured by indoor air quality, lighting characteristics, and background ambient noise levels.

It was and is quite common practice that in-plant offices for industrial facilities used through-the-wall or bar room style air conditioning units with little or no provision for outside air ventilation. The odds are ten to one that the building you are in now has packaged rooftop air handling units with throwaway filters and fixed minimum outside air dampers. The filters are 10 percent efficient at best and are probably clogged. The outside air damper is probably shut to save energy, and the unit is virtually inaccessible for regular inspection and maintenance.

If you suffer from nausea; headaches; dry mucous; inflamed membranes; eye, nose, or throat irritation; drowsiness; or dry skin while in your place of employment, then you are probably suffering from building related illness or sick building syndrome, which is the popular euphemism today. When more than 20 percent of the building occupants have these symptoms, then you probably do have a serious IAQ problem.

In a recent article in the *Journal of the American Institute of Architecture*, warning was given that the single most important area of liability litigation facing building designers is the environmental performance of buildings. We solved the energy cost equation with smaller windows, lower lighting levels, better thermal insulation, and reduced levels of air circulation and makeup air.

I am going to put on my architect/engineer hat for the moment and deplore the ongoing trend in the construction industry to denigrate proper engineering of building environments. A large percentage of speculative office buildings today are not designed by professionals but are put together on a design/build or prescriptive basis with bottom line cost as the only criterion.

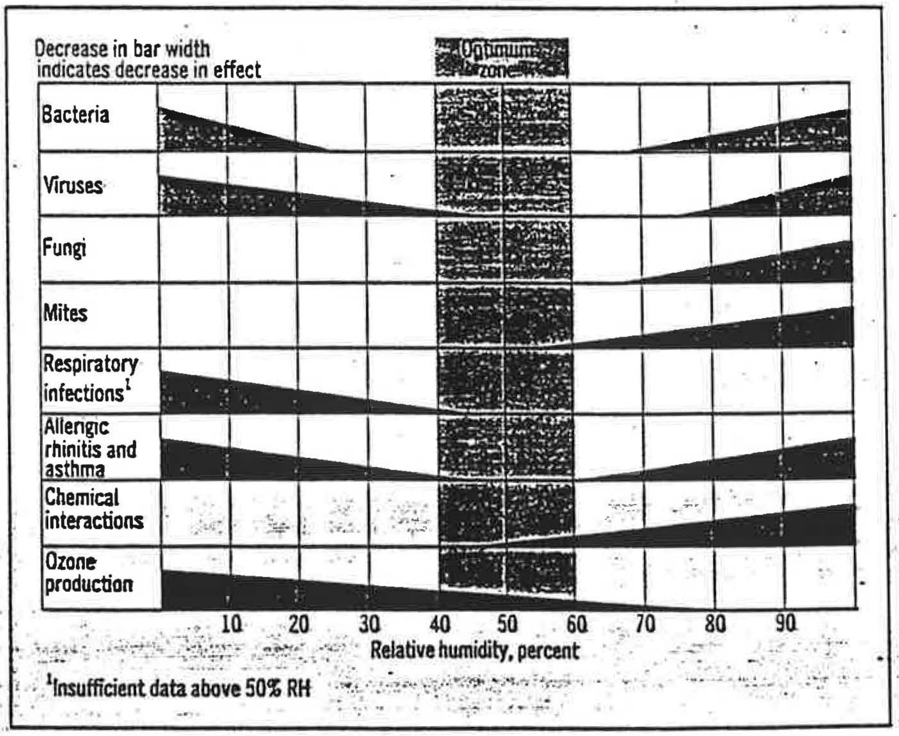
A survey of 5000 buildings by the World Health Organization indicated that 30 percent of all new or remodeled office facilities had inadequate ventilation and provided poor comfort conditions for their occupants. It is less than amusing to hear that even the EPA is having problems with its own buildings in Washington, D.C., having converted an existing apartment building over to offices (National Public Radio, "All Things Considered").

This article will explore some of the IAQ issues involved and attempt to define comfort in today's idioms. What is meant by sick building syndrome or building associated illness? How do you define indoor air quality? How does one address proper air distribution?

Indoor air quality

Simply defining air quality is complicated. You have to deal with such terms as transient exposures, stay times, threshold limit values, biological exposure indices, susceptibility, "Selyes general adaptation syndrome," and now "olfs" and "pols," courtesy of Professor Ole Fanger of The University of Denmark. Air quality cannot currently be defined by biochemical or biological components. The characteristics of air, bioeffluents of the human body, and the composition of collective outgassing of materials combine to affect human comfort. The susceptibility of individuals and interaction with these materials and their physiological and toxicological effects becomes the real measure of acceptability. In fact, this is how ASHRAE defines acceptable indoor air quality: "that providing acceptable comfort levels of 80 percent of test subjects."

ASHRAE has been very active in this field for years. Recent developments come out of the presidential



1 Optimum relative humidity ranges for health.

Theodor O. Sterling & Associates, Ltd., Vancouver, B.C. Published in: Sterling et al. (1985) ASHRAE Transactions, Vol. 91, Part 1, 1985.

Table 2—National outdoor air ambient air quality standards

	Long term concentration averaging			Short term concentration averaging		
Contaminant	mg/m³	ppm	Time	mg/m³	ppm	Time
Sulfur dioxide	80	0.03	1 year	365	0.14	24 hr
Carbon dioxide	0.54	300	1 year			
Carbon monoxide				40,000	35	1 hr
				10,000	9	8 hr
Ozone (oxidants)				235	0.12	1 hr
Nitrogen dioxide	100	0.055	1 year			
Lead	1.5		3 mo.			
Total particulate*	75	—	1 year	260	—	24 hr
Radon	0.2 picocuries per liter					

*EPA—50 to 60 $\mu g/m^3$

Information courtesy of U.S. Environmental Protection Agency.

Table 3—Guidelines for selected air contaminants of indoor origin.

Contaminant	Concentration	ppm	Exposure time
Carbon dioxide*	1.8 g/m^3	1000	Continuous
Carbon monoxide	55 mg/m^3	50	8 hr
Chlordane	55 $\mu g/m^3$	0.0003	Continuous
Ozone	100 $\mu g/m^3$	0.05	Continuous
Radon**	0.027 WL		Annual average
Nitrogen dioxide	9 mg/m^3	5	Continuous
Sulfur dioxide	13 mg/m^3	5	
Total suspended particulates	100 $\mu g/m^3$		1hr

*Threshold value—600 ppm (NIOSH)
**3200 picocuries

Information courtesy of OSHA final rule, Air Contaminants—Permissible Exposure Limits.

committee on environmental health issues, the new Standard 62-89—*Ventilation for Acceptable Indoor Air Quality*, position papers and position statements on indoor air quality, and frequent publications resulting from annual international IAQ seminars since 1985. Standard 55 establishes thermal environmental conditions for human occupancy, Standard 52 establishes methods for testing air cleaning devices, and Standard 90A developed energy conservation standards for new buildings. We are obviously not lacking information. Table 1 provides a listing of organizations with major involvement in these issues and key publications.

To put things in perspective, it is necessary to understand the basic elements in outdoor air (at one time euphemistically called "fresh air"). Table 2 provides a listing of the EPA's national outdoor air ambient air quality standards. These relate to typical urban areas. Obviously, conditions are far worse in some big city locations. Conversely, rural areas can anticipate a higher level of quality.

Tables 3 and 4 provide listings of commonly found indoor air pollutants and recommended maximum exposure limits. In most instances, these "comfort" standard limits are nominally 10 percent of threshold limit standards established by the Occupational Health and Safety Administration. It should be noted that these one-tenth values are a guideline for individual volatile organic compounds (VOCs) and may not be acceptable where the collective effects of several VOCs are present.

It is an anomaly of this industrial era that ozone has such a critical influence on our environment. Too little of it (together with carbon dioxide) is contributing to the greenhouse effect and ultraviolet contamination. Too much of it as direct exposure can cause severe toxicological effects.

While a single pollutant element may in itself not cause significant health effects, the composite actions of multiple pollutants can seriously impact human respiratory systems, leading to susceptibility to pneumophilia and other viral infections.

While discussions on individual rights associated with smoking may evoke considerable emotional reactions, there is no question that passive, secondary, or environmental tobacco smoke has a considerable effect on ambient air quality. Table 5 shows the results of studies that have been made in several commercial office buildings to evaluate the concentrations of particulates, carbon monoxide, carbon dioxide, and nicotine resulting from

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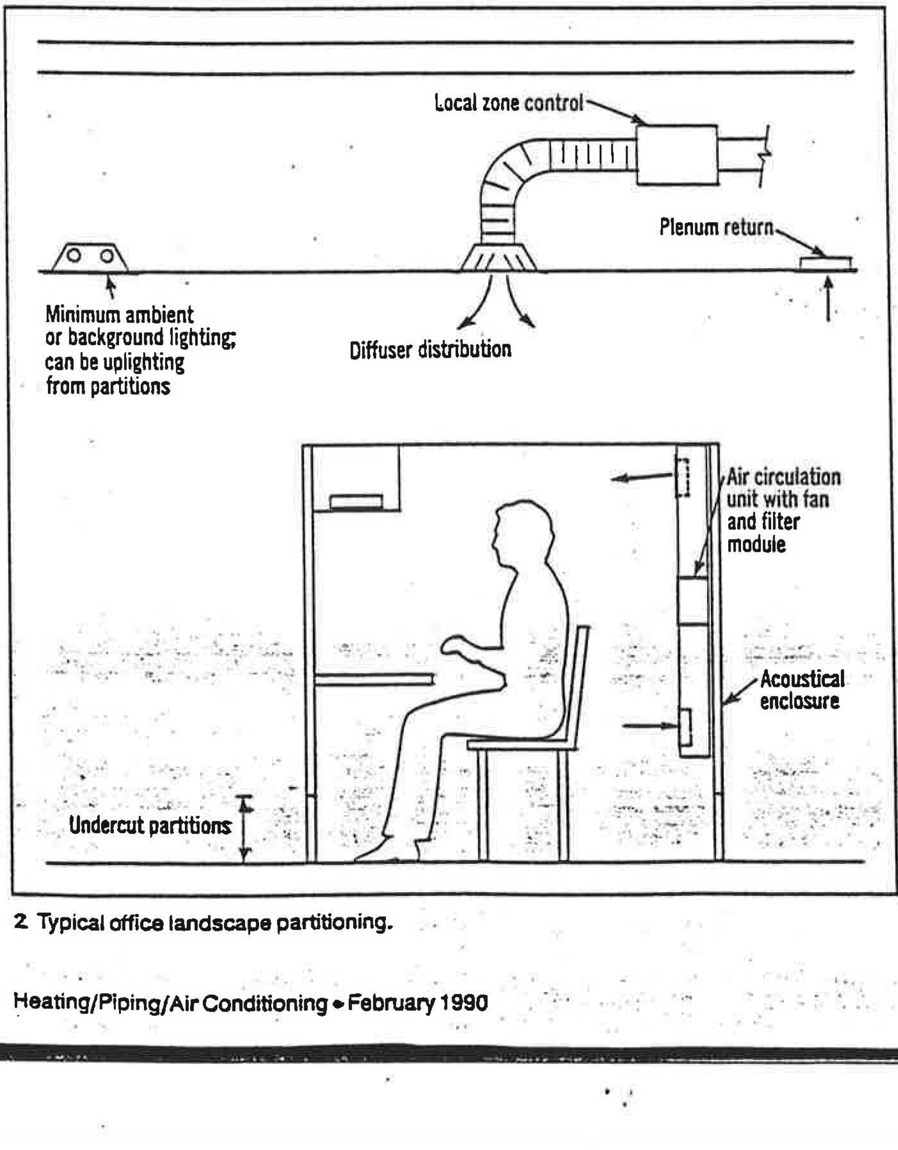

2 Typical office landscape partitioning.

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Table 4—Common indoor air contaminants.

Contaminant	Concentration
Aspergillous (microbial aerosol)	(Airborne dust origin)
Formaldehyde (plywood and synthetics)	0.05 to 0.06 mg/m^3
Volatile organic compounds (furniture and draperies)	30 to 50 mg/m^3 (see below) (5 to 50 ppm)
PCBs (rugs/lubricants)	4.5 μg/m^3
Asbestos fibers (fireproofing)	(5 μ or larger) 0.2 to 2.0 fibers/cm^3
Ammonia (cleaning agents)	3.5/mg/m^3
Biological aerosols (sprays)	—
Outgassing (plastics)	—
Benzyl chloride (vinyl)	0.1 ppm, 0.5 mg/m^3
Phlhalates (wall coverings)	—
*Tobacco smoke	0.1 to 0.15 mg/m^3
Legionellous (virus)	Airborne/moisture particle related virus
Carbon tetrachloride (cleaning agents)	20 ppm

*Passive or secondary smoke

Common volatile organic compounds (VOCs)

Toluene	10 ppm
Methylene chloride	10 ppm
Benzene	1 ppm
Acetone	75 ppm
Styrene	5 ppm
Refrigerant	50 ppm
Dioxane	2.5 ppm

Concentrations shown represent one-tenth of time weighted average exposure limits established by OSHA and are the maximum levels recommended in ASHRAE Standard 62 for human comfort.

smoking.

Obviously, the level of contaminants varies subject to the number of cigarettes smoked and the general ventilation rates. Regardless, both the smoker and nonsmoker are subject to involuntary exposure to high concentrations of materials that reduce indoor air quality.

Ventilation rates

In tests conducted by the National Institute of Standards, the outside air change rates measured in a large number of modern office buildings (using tracer gas or carbon dioxide dispersion techniques) were typically in the range of 0.6 to 1.2 air changes per hr with the predominant average being 0.9 air changes per hr. Put in terms of a typical office building with 9 ft ceilings, this represents 0.135 cfm per sq ft. Given a fairly general standard air conditioning rate of 0.6 to 1.0 cfm per sq ft *total* ventilation rate (4.0 to 6.5 air changes per hr), this represents 22.5 to 14 percent outside air and, at an occupancy rate of 150 sq ft per person, is equivalent to 20 cfm per person. That is right on the money per ASHRAE Standard 62-89—*Ventilation for Acceptable Indoor Air Quality* as a *minimum* recommended ventilation rate.

The standard recommended minimum levels of outdoor air include the guidelines shown in Table 6. Standard 62-89 also provides guidelines for minimum ventilation times required to purge areas before and during occupancy based upon physical activity levels.

One might ask, "Why not significantly increase the amount of outside air for dilution purposes?" The answer is equally simple: energy—and energy costs money! Typical costs for handling 1 cfm of outside air in an office air conditioning system are in the range of $2.50 to $4 per cfm per annum dependent upon location and occupancy period.

It should also be remembered that ventilation in itself is not the solution to indoor air quality. It can help to relieve or diminish the effects of contaminants, but the source of these elements needs to be found and resolved.

Humidity

Little attention is paid to humidity control other than for institutional buildings and special occupancy areas such as computer rooms. Yet, humidity control plays a large part in providing human comfort. It is a lot more than simply eliminating static electricity at low RH and mugginess at high RH. Humidity levels can play a significant role in bacterial, viral, and fungal growth. In addition, humidity can have a significant effect on emissions from drapes and carpeting by controlling their brittleness and dust generation.

Fig. 1 (courtesy of T. D. Sterling, professor of interdisciplinary studies at Simon Fraser University) shows optimum ranges of relative humidity for health. It clearly illustrates the effects that humidity levels can have on our environment; yet many office buildings have little or no control on low level ranges of humidity in winter. The use of variable volume systems with bypass control or of chilled water temperature reset control also permits high levels of humidity to be reached in summer.

Another aspect of humidity control that requires increasing scrutiny is the humidity generating or eliminating equipment itself. It is now recognized that standing water in cooling coil drain pans and humidifier pans can be a virulent source of bacteria and disease. There is a general trend in the industry to recommend abandonment of the use of sprayed coil cooling systems, air washers, and direct evaporative cooling systems due to the difficulty in adequately controlling and maintaining the systems to avoid biological growths. Use of treated steam or treated water as a humidity source has also been found to build up chemicals in the occupied space with subsequent effect on human health. In addition to utilizing new tech-

Table 5—Ambient air quality, typical values in buildings.

	Nicotine, μg/m^3	Particulate μg/m^3	Carbon monoxide, ppm	Carbon dioxide, ppm
General smoking	4 to 5	70 to 80	2 to 3	700 to 750
Designated smoking	30 to 70	350 to 400	4 to 5	950 to 1000
Nonsmoking	0 to 2	50 to 60	1 to 2	600 to 700

nologies for humidity control, it is also obvious that good housekeeping practices are required.

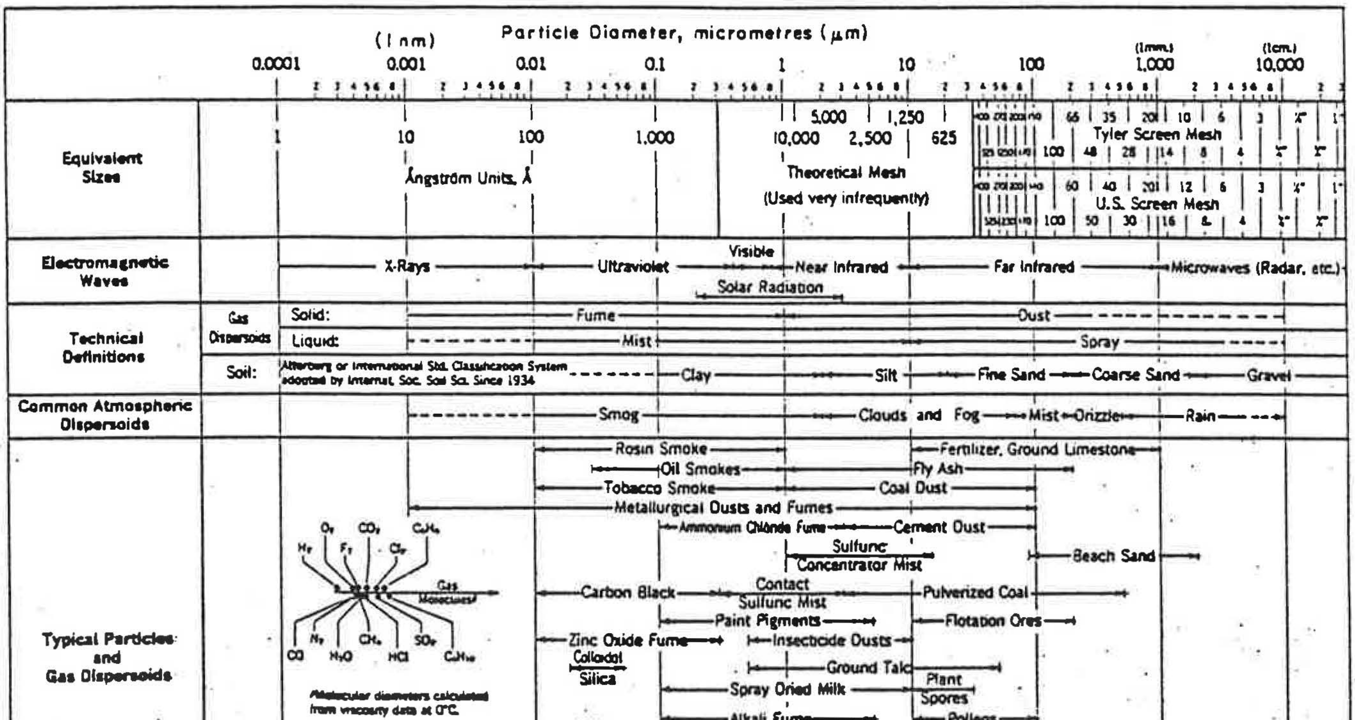
Epidemiology studies have shown significant decreases in absenteeism and respiratory infection occurrences in occupants of humidified buildings as compared to nonhumidified buildings.

Air circulation

It is no longer enough to supply air to the space properly tempered, filtered, and humidified at adequate outside air and total air change rates. You need to get it to the working zone. The primary concern in air distribution patterns for offices has always been diffusion to avoid discomfort from cold drafts, etc. You may be familiar with the corona pattern of diffuser air flow nicely hugging the ceiling and providing gentle air distribution. The following elements have impacted the effectiveness of these systems:

- The total circulation rate has been reduced as a result of more energy efficient building envelopes and lower lighting levels.
- The effectiveness of ventilation air distribution has been reduced with much of it being short-circuited back to toilet exhausts or return air inlets.
- The widespread use of landscape office partitions has disrupted the air circulation pattern, causing stagnant pockets of contaminated air to be trapped in the vital occupancy zone.

The total circulation rate used to be determined solely by design load. As these loads reduced, minimum circulation rates were established below which stagnant conditions and complaints could be anticipated. Typically, these were in the range of 0.6 to 1.0 cfm per sq ft, 4 to 6 air changes per hr. Variable volume systems have cut into these rates still further, and the growing use of low temperature air (from ice thermal storage systems) will reduce primary air movement still further. This brings back the



3 Characteristics of particles and particle dispersoids.

need for terminal induction units or fan powered terminal boxes to maintain local or secondary circulation levels, albeit with the accompanying capital costs, operating costs, maintenance costs, and acoustical issues.

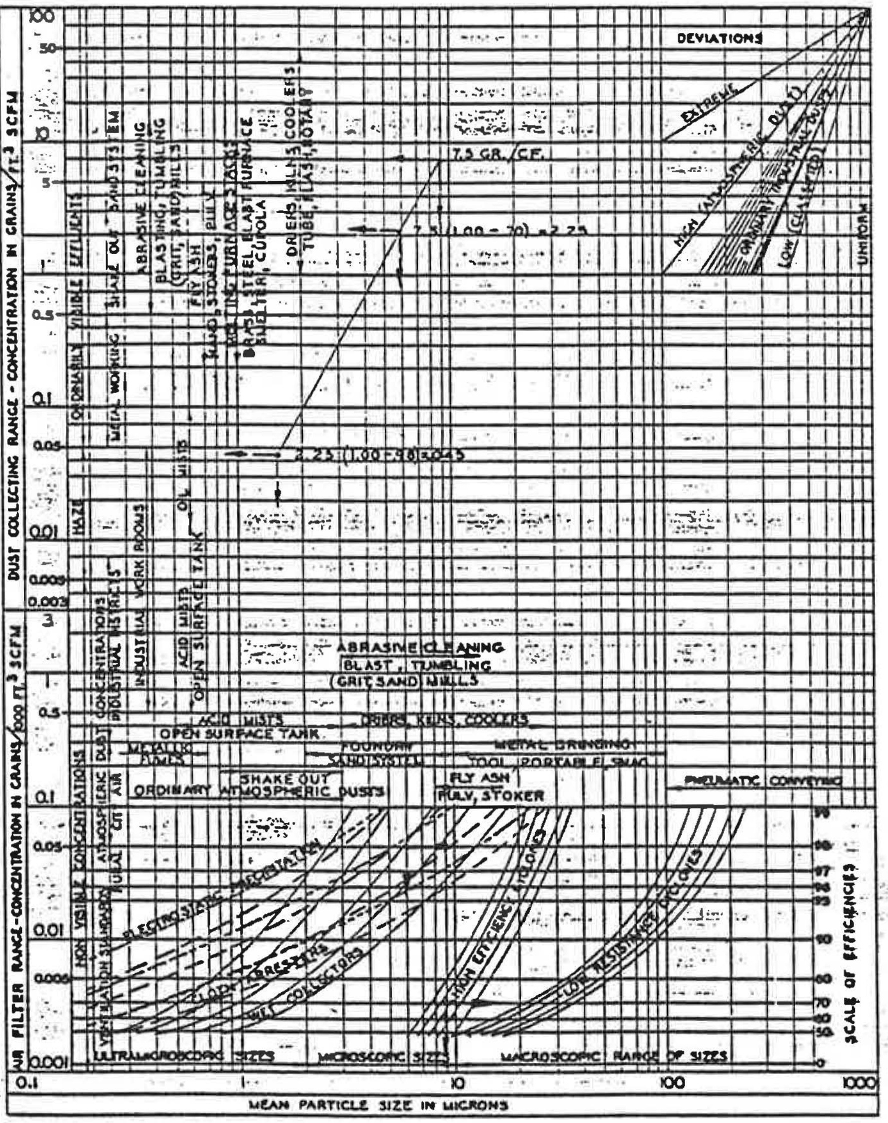
The installation of landscape partitioning can seriously disrupt air distribution. Tests in Canadian office buildings have shown that, if not properly designed, partitions will create stagnant pockets of air, particularly since most of the gases, odors, biocides, etc., are heavier than air. One solution is to ensure a minimum undercut on the partitions of at least 18 in. Another and probably better solution is to provide local circulation within the partitioned area. Primary air will provide filtered outside air makeup cooled, humidified, or dehumidified sufficiently to maintain the required comfort levels. The local circulation systems will ensure the distribution of that air to the working zone (Fig. 2).

Air filtration

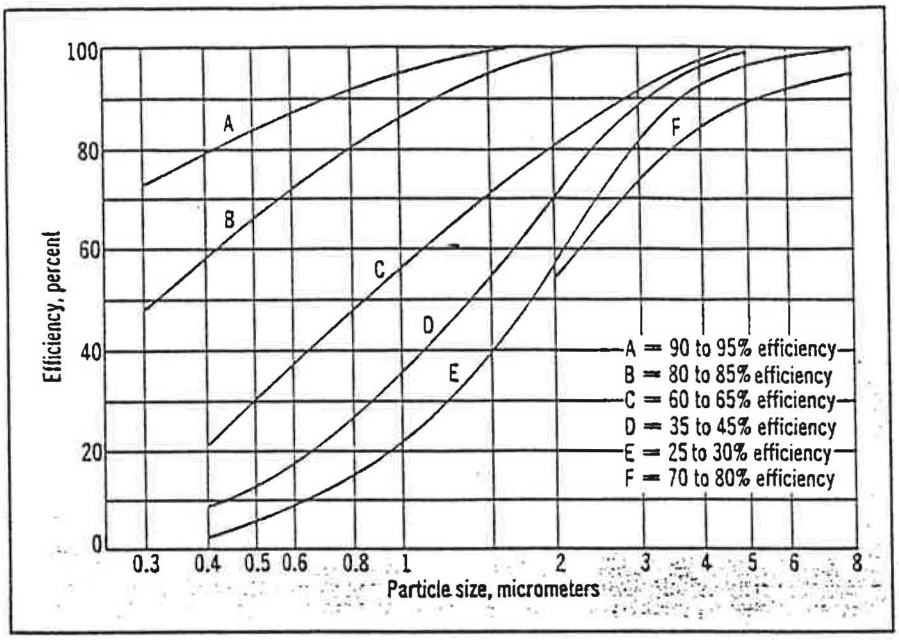
For all intents and purposes, air filtration to improve indoor air quality is virtually useless. That is not to say that air filters should not be installed. They are necessary from a basic housekeeping and cleanliness standpoint; but anything less than high efficiency particulate air (HEPA) filtration is totally ineffective in removing tobacco smoke, bacteria, fungi, and aerosols. For contaminants such as gases and odors, other types of treatment—such as activated charcoal filtration—are required.

If you look at the typical ranges of micron sizes for different contaminants, most of these are submicron, predominantly in the 0.005 to 0.5 micron range (Fig. 3, courtesy of Stanford Research Institute, and Fig. 4, courtesy of American Air Filter). If you then look at typical filter efficiencies (Fig. 5) compiled from manufacturers' data on filter efficiencies, only high efficiency (80 to 95 percent) filters are at all effective. The more standard 1 or 2 in. throwaway filter panel is not even rated in this category and if it was would be less than 5 percent effective. Field tests indicate that use of 55 percent efficient (NBS dust spot) filters can maintain particulate levels in the order of 130 ppm in typical office buildings while 95 percent efficiency filters can reduce this level to 75 ppm. Despite this, you will not typically see HEPA filters installed in office buildings (too expensive to maintain), and the 1½ to 2 in. WG pressure drop is considered too costly an energy penalty; nor will you see carbon absorption filters for the same reason. While electrostatic filters *can* be effective in aerosol and smoke removal, they do require frequent maintenance (generally hot water/biocidal washing) to prevent ozone generation and agglomerated dirt reinjection into the system. None of these filtration methods is effective in handling gaseous emissions, which can typically only be removed by absorbing or oxidation. Similarly, mechanical ventilation systems cannot generally effectively remove agents causing airborne bacterial infections but can only propagate and distribute them.

In general, we have opted for outside air dilution as the most effective way to maintain indoor air



4 Range of particle sizes, concentrations, and collector performance.



5 Approximate efficiency versus particle size for typical air filters.

quality. Even then, I urge that air filters be installed with not less than 35 to 45 percent dust spot efficiencies to prevent dirt buildup in both the ventilation systems and on building finishes (either of which can lead to bacteria and viral spore buildups). Areas with known high level emissions of contaminants should be directly exhausted.

Maintenance

Once the system is installed, *commissioned*, and certified to be performing at the designed level, maintain it by following these recommendations:

- Keep up basic housekeeping to avoid dirt buildup, subsequent re-entrainment, and bacterial spore development. Review cleaning compounds and use wisely.
- Clean out cooling unit drain pans.
- Replace air filters only with proper media quality.
- Maintain levels of biological and corrosion treatment in cooling towers to reduce fungus or legionellous bacteria.
- Control levels and use of pesticides or fumigants and ensure proper ventilation rates to purge excess materials before occupancy.
- Regularly clean electrostatic air filters used for smoke control.
- Avoid placing obstructions in front of ventilation supply or return outlets.
- Place process equipment such as copiers and blueprint machines in rooms with exhaust (not recirculated) ventilation.
- Increase ventilation purge rates following building renovation, painting, carpeting, etc.
- Train personnel in the proper operation and maintenance of the building environmental systems.
- Maintain control systems to ensure proper operation.
- Thoroughly investigate all causes and effects when revising control sequences or set points.

Recognize that improper maintenance has been cited by NIOSH as the principle cause of 75 percent of sick building syndrome complaints.

Conclusion

What all this is meant to suggest is that there is no single or simple solution to maintaining human comfort. Rather it is a collective effort of design strategies that encompass all elements of the environment itself. There are some simple guidelines that will minimize the potential for trouble. The simplest of all is: *Don't take shortcuts!* Not in order of priority, some of these key elements can be stated as follows:

- Ensure that the building envelope can control infiltration and exfiltration levels.
- Minimize the emissions from synthetic building finishes such as wall coverings and carpeting.
- Provide source exhaust ventilation at critical containment points such as blueprint machines, copying equipment, dedicated smoking areas, etc.
- Review prevailing wind conditions and air current patterns around buildings.
- Locate outside air intakes so as to prevent re-entrainment of contamination sources such as truck docks, toilet exhausts, and plumbing vents.
- Provide adequate outside air ventilation to all areas of the building at not less than 20 cfm per person.
- Maintain a minimum total air circulation rate of 4 to 6 air changes per hr.
- Design to prevent stagnant pockets of air.
- Install and maintain air filtration systems with not less than 35 to 45 percent dust spot efficiencies and preferably 80 to 85 percent efficiencies.

Table 6—Recommended levels of outdoor air (from ASHRAE Standard 62-89)

Application	Occupancy, per 1000 sq ft	cfm per person	cfm ft
Patient rooms	10	25	0.2
Medical procedure rooms	20	15	0.3
Office space	7	20	0.1
Conference rooms	50	20	1.0
Corridors			0.0
Smoking lounges	70	60	4.2
Auditoriums	150	15	2.2
Classrooms	50	15	0.7

- Be aware of potential viral bacteria contamination of cooling coil drain pans and cooling tower systems and design in remedial and treatment methods.
- Become knowledgeable of the potential problems and their solutions.
- Commission the building services upon completion of construction so as to achieve the original design objectives.
- Operate the building cognizant of the issues and maintain the environment. Ω