Are Indoor Air Pollutants Threatening the Reliability of Your Electronic Equipment?

By HELEN C. SHIELDS,
Scientist, and
CHARLES J. WESCHLER, PhD
Senior Scientist,
Advanced Environmental Solutions,
Bellcore,
Red Bank, N.J.

The likelihood of costly failures of electronic equipment can be reduced when volatile organic compounds (VOCs), airborne particulates, and gaseous pollutants are properly addressed as discussed in this article

Numerous studies have examined the effects of airborne pollutants on people. These studies have demonstrated how airborne pollutants can cause discomfort to building occupants in the form of headaches, nausea, itchy eyes, lethargy, and other irritating effects. Not widely realized is the fact that the same pollutants that affect people can adversely impact electronic equipment (Weschler and Shields, 1991). That is, sophisticated electronic equipment is sensitive not only to temperature and humidity but also to airborne contaminants. The focus of this article will be the effects of volatile organic compounds (VOCs), airborne particles, and inorganic gases on such equipment. While the authors deal with this subject from the perspective of the telecommunications industry, much of this article's content is applicable to other types of electronic installations found in commerce and industry.

Failures due to pollutants

Volatile organic compounds (VOCs) are common constituents of indoor air. VOCs can contribute to the failure of electronic equipment in both switching offices and data centers. The level of these organics can also be a useful indicator of the need to ventilate. The failure of electronic equipment as a consequence of exposures to VOCs can occur by one of several mechanisms.

- If relays are contained in the equipment, VOCs can promote arcing between relay contacts-leading to increased contact erosion (contact activation). Excessive circuit noise occurs after the arcing process has removed the thin precious metal layer and exposed the base metal. For activation processes a value of approximately 500 μg per cu m has been reported (Gray, 1978) as the lower critical exposure. It is prudent to keep VOC levels one to two orders of magnitude below this threshold.

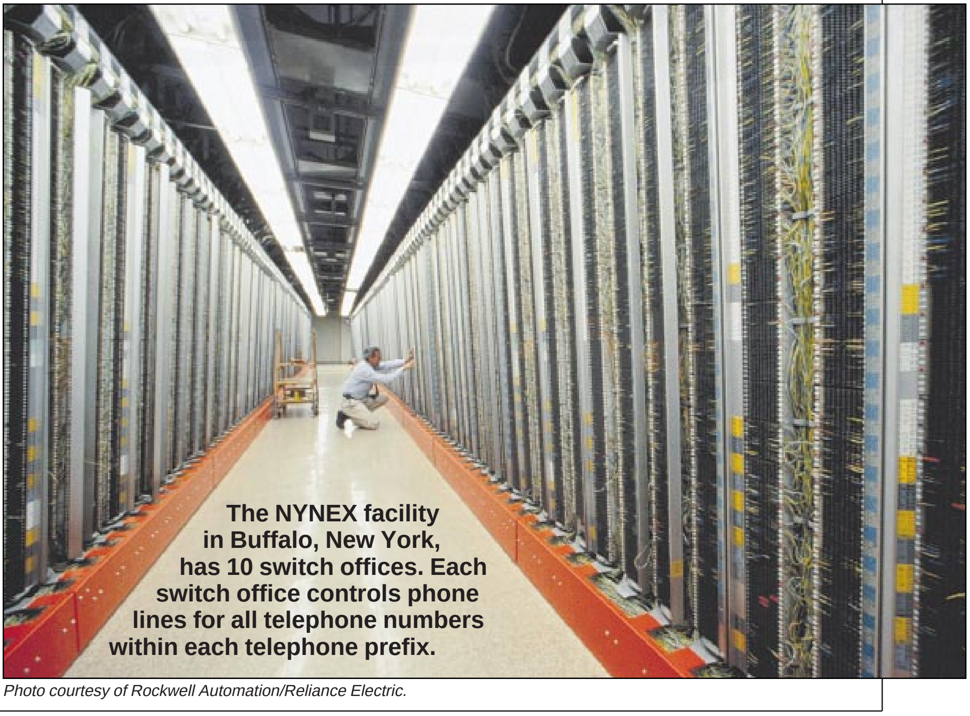
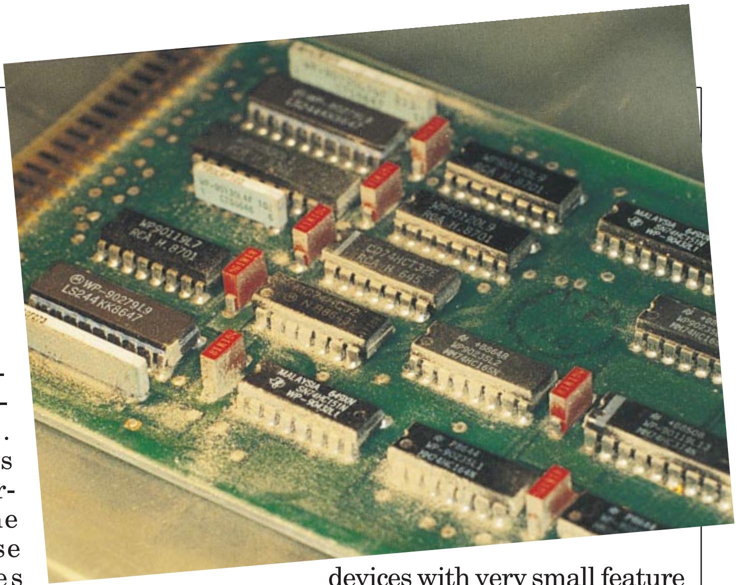

The NYNEX facility in Buffalo, New York, has 10 switch offices. Each switch office controls phone lines for all telephone numbers within each telephone prefix.

Photo courtesy of Rockwell Automation/Reliance Electric.



1 Circuit pack contaminated with airborne particles.

- A second failure mechanism involves polymeric films derived from VOCs. Such films, sometimes referred to as "frictional polymer," can produce unacceptably high resistance between contact surfaces (Hermance and Egan, 1958; Reagor and Seibles, 1981). Equipment cooling fans, building ventilation fans, and even motor vehicle traffic can cause sufficient vibratory motion to form a frictional polymer. Frictional polymer is an increasing concern as the forces between mated connectors, as well as the current they carry, decreases.

VOCs can condense on tape heads. This increases the probability that fine particles will stick to the heads, causing subsequent computer head crashes and disc drive failures. Other magnetic storage systems can be affected in a similar manner.

- Airborne particles can also cause various types of failures in electronic equipment. The nature of these failures varies with the composition and size of the particles. The mass distribution of airborne particles tends to be bi-modal (Finlayson-Pitts and Pitts, 1986) with a minimum in the distribution at about 2.5 µm diameter. The terms *fine* and *coarse* are commonly used for particles smaller and larger than 2.5 (µ diameter, respectively. These particles tend to have different physical properties, chemical compositions, and sources. When telephone switching equipment, as well as other electronic equipment, was primarily mechanical or electro-mechanical, coarse particles were responsible for most of the failures. Today's digital equipment tends to be more sensitive to fine particulate contamination.

Fine particles can collect on the surfaces of circuit packs, bridging a gap between two conducting paths that are intended to be isolated from one another (Fig. 1). As the relative humidity rises above the deliquescence point (critical relative humidity) of the salts associated with these fine particles, the "dust-bridges" become moist. This increases the flow of current across the bridges. These consequences are sometimes referred to as "hygroscopic dust failures"(Weschler and Shields, 1991; Sandroff and Burnett, 1992) and have cost the telecommunications industry hundreds of millions of dollars.

Various types of corrosion (chemical, electrochemical and galvanic) can be promoted by the water-soluble salts associated with fine-mode particles. Oxide films on many metals are easily broken down by the chloride salts contained in fine particles (Comizzoli et. al., 1986). Chloride salts tend to adsorb moisture readily and have high mobilities in aqueous solutions. The latter property further increases the corrosivity of chloride containing particles in electric fields.

TABLE 1—Mechanisms by which particulate contamination can contribute to failures in electronic equipment.

FAILURE MECHANISM	PARTICLE SIZE OF CONCERN*
Current leakage	Fine
Shorts	Fine and coarse
Corrosion	Fine
Image charging	Fine
Stress corrosion cracking	Fine
Open contacts	Coarse
Connector wear	Fine and coarse
Abrasion of magnetic media	Fine and coarse
Head crashes	Fine

*Fine particles—less than 2.5 am diameter; coarse particles—2.5 to 15 am diameter

In the case of certain very large scale integration (VLSI) devices, the corrosion of as little as a nanogram of material can cause failures. Fine-mode ionic contaminants, which have accumulated on high voltage devices with very small feature sizes, can also create stray fields (image charging) and lead to the malfunction of such devices.

As connectors are inserted and removed, the abrasive particles on the surfaces of connectors can promote wear. Since the precious metal plating on connectors is very thin—approximately 30 µin.—even a small amount of wear can cause failures. Coarse-mode particles are more likely to be abrasive than fine-mode particles due to their chemical compositions.

Particles can cause failures in magnetic storage devices. This is more of a problem with floppy drives than hard drives. In each case, the read/write head of the drive is sensitive to particulate contamination. Hard drives tend to be well protected from the influx of particles. Floppy drives, however, are not as well sealed. Particulate contamination (both fine and coarse) of magnetic tape heads is also a serious problem, causing excessive wear of the magnetic tape passing over the head. Table 1 summarizes some of the problems caused by airborne particles within telecommunications facilities.

Unlike the motions of larger particles, the motions of fine-mode particles are not influenced as strongly by gravity. Instead, fine particulate motion is largely governed by diffusion processes and can be strongly affected by electric fields, thermal gradients, and air currents. Hence, fine particles are as likely to accu-

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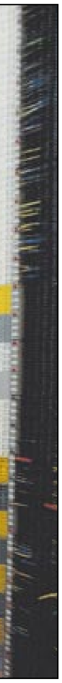

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mulate on vertical and horizontal surfaces and will preferentially deposit near high electric fields on circuit packs. As a consequence of their size and small mass, fine particles are much more difficult to filter than coarse particles.

TABLE 2—The 10 most abundant VOCs detected within switching offices, data centers and administrative offices. The compounds are rank ordered, and their geometric mean concentrations (mg/m^3) are shown in parentheses.

SWITCHING OFFICE	DATA CENTER	ADMINISTRATIVE OFFICE
D5* (7.0)	D5* (26)	D5* (40)
n-undecane (6.5)	n-undecane (16)	n-pentadecane (13)
Toluene (4.8)	Toluene (10)	n-hexadecane (11)
Xylene (m&p) (4.3)	n-decane (9.8)	n-tetradecane (11)
n-tetradecane (4.1)	D4* (9.4)	D4* (10)
n-decane (4.1)	n-dodecane (9.3)	n-undecane (9.1)
n-dodecane (3.8)	n-pentadecane (8.5)	n-dodecane (6.9)
n-pentadecane (3.3)	n-tetradecane (7.9)	Limonene (6.2)
1,2,4-Trimethylbenzene (3.2)	n-hexadecane (7.6)	Toluene (5.7)
Xylene (o) & Styrene (2.8)	Xylene (m&p) (6.7)	1,2,4-Trimethylbenzene (5.0)

*D5 = decamethylcyclopentasiloxane; D4 = octamethylcyclotetrasiloxane

- Inorganic gases that can contribute to failures include ozone, nitrogen oxide, and various acidic species. Ozone is the most powerful oxidant found in switchrooms and data centers. It promotes cracking of stressed rubber (*e.g.,* rubber O-rings, rubber seals, and butyl insulation on power cords) and attacks various paints, pigments, elastomers, and plastics. Ozone can also react with certain indoor compounds to generate more harmful products such as nitric acid, nitrous acid, various organic acids, and free radicals such as the hydroxyl, hydroperoxy, and nitrate radicals (Weschler and Shields, 1997).

Acidic gases, especially nitric acid (HNO_3) and hydrogen chloride (HCl), can attack metallic components in electronic equipment. Most buildings contain mechanical ventilation systems with filters designed to remove at least a fraction of the airborne particles. However, very few of these installations have any control measures to remove gaseous pollutants such as ozone, hydrogen chloride, nitric acid, or the other oxides of nitrogen.

Discussion of pollutants

- *Volatile organic compounds*—In a recent study, VOCs were simultaneously measured indoors and outdoors at 50 sparsely occupied telecommunication switching offices, nine variably occupied data centers, and 11 densely occupied administrative offices (Shields, Fleischer, and Weschler, 1996). Comparisons among the three building types as well as within each of the building types showed the influence of ventilation, occupants, and other sources. The switching and administrative offices were better ventilated than the data centers, but the administrative offices had more and stronger sources than the switching offices.

Table 2 shows the 10 most abundant compounds found at a given building type. For each building type, the compounds are rank ordered, and their geometric mean concentrations (µg per cu m) are shown in parentheses. (Compounds listed for a given building type were almost always detected within that building type.)

Similar compounds were detected in various facilities, but the order of their relative abundance varied with building type. The most prevalent compound detected at all three locations was D5, a compound associated with human occupants and their use of personal care products. There were fewer occupants in the switching offices. This was reflected in the concentration of D5 (approximately 7 µg per cu m); the concentration of this compound at the administrative offices was six times higher (approximately 40 µg per cu m).

People had a marked effect on the VOC concentrations. This is apparent from the top 10 compounds detected at the administrative offices. The compounds n-pentadecane, n-hexadecane, and n-tetradecane are associated with hand and body creams and moisturizing

TABLE 3—Possible sources of selected VOCs.

COMPOUND	POSSIBLE SOURCE(S)
Toluene	Glues, aromatic solvents, smoking
Perchlorethylene	Dry cleaned clothing, degreasers
Linear, branched, & cyclic alkanes from n-heptane to n-dodecane	Aliphatic solvents (paint thinner, mineral spirits, naptha
Alpha-pinene	Pine scented cleaners or "air freshners"
Limonene	Lemon scented cleaners or "air freshners", terpene based solvents, lemons and oranges
D4*, D5*	Personal care products-especially underarm deodorants; thermal decomposition of dimethyl silicones
n-Dodecane to n-hexadecane	Liquid petrolatum from hand and body creams, moisturizing soaps
Alkyl benzenes (*e.g.,* xylenes, ethyl benzene, trimethylbenzene, etc.)	Aromatic solvents (rubber cement, adhesives, coatings, resins), smoking, combustion
Styrene	Styrene polymers (Styromfoam, ABS, Noryl), smoking , adhesives

*D5 = decamethylcyclopentasiloxane; D4 = octamethylcyclotetrasiloxane soaps, while limonene is a lemon scent found in personal care products as well as cleaning products and solvents. The aromatic compounds such as toluene, ethyl benzene, and xylene are the most active contributors to the formation of frictional polymer (see above). Some of the sources for the VOCs in Table 2 are listed in Table 3.

● *Airborne particles*—Fine particles are derived primarily from combustion processes (motor vehicles, home heating, smoking, and cooking). Coarse particles are derived primarily from mechanical processes such as cutting, grinding, abrasion, and wind-promoted erosion. As previously noted, particles can cause equipment failures-especially fine particles. Proper filtration can remove a significant fraction of particles from the air. Some of the major benefits derived from filtration are summarized in Table 4.

Filtration is beneficial, but there are associated costs, which include design costs; material costs—filters, frames, etc.; labor costs associated with installing and replacing the filters; and the cost of the fan energy required to move air through the filters. All else being equal, as the removal efficiency of a filter increases, so does the cost. When efficient filters are used, the fan energy is normally the largest annualized cost associated with filtration.

Recently, a new type of high-efficiency filter (referred to as "high-efficiency, low pressure drop," "mini-pleat," or "extended surface area") has become available. Results from an actual field test of such filters have demonstrated that, compared to traditional filters with a similar dust spot rating, these filters:

•Have a longer service life—approximately 140 percent longer.

•Present less average resistance to air flow—approximately 20 percent less over their service life.

•Have comparable sub-micron particulate removal efficiencies.

Mini-pleat filters are an example of a product that initially costs more but saves money in the long-term. Furthermore, in facilities where the existing fan motor would be unable to accommodate traditional high-efficiency filters, mini-pleat filters may present an acceptable alternative to much less efficient filters.

Although the outdoor air contains fine-mode particles that contribute to the soiling of equipment, it is still prudent to use outdoor air for ventilation. Nonetheless, it would be advantageous to minimize the use of outdoor air when the outdoor particle concentrations are unusually high. At a field trial in Burbank, Calif., we used an optical particle counter to monitor the outdoor concentrations of fine-mode particles (Weschler, Shields, and Shah, 1996). When the outdoor concentration exceeded a preset value, the outdoor air damper would partially close, reducing the amount of outdoor air entering the building. In effect, the position of the damper was based on the concentration of outdoor particles as well as the outdoor temperature. As a consequence, the average indoor concentration of fine-mode particles was significantly reduced within the facility, but the indoor concentrations of pollutants with indoor sources were not significantly compromised.

TABLE 4—Benefits of filtration.

■ **Reduced failure rates**—improved equipment performance and reliability

■ **Reduced equipment soiling**—less vulnerable to loss of HVAC system

■ **Reduced soiling in office area**—lower housekeeping costs

■ **Reduced soiling of lighting fixtures**—more efficient illumination

■ **Reduced soiling of cleaning coils**—less frequent coil cleaning and lower energy costs

● *Inorganic gases*—Certain types of office equipment as well as electrostatic precipitators are known to generate ozone. In our studies, however, most ozone detected indoors has been generated outdoors and transported in through the ventilation system. If there are no indoor sources, indoor ozone levels typically range from 20 to 30 percent of outdoor values in moderately ventilated office space to 50 to 70 percent of outdoor levels in highly ventilated classrooms, conference rooms, and dining areas (Weschler, Shields, and Naik, 1989 and references therein; Weschler and Shields, 1994a). During the summer in highly ventilated settings, it is not unusual to see outdoor ozone levels higher than the National Ambient Air Quality Standard (NAAQS) of 120 ppbv.

When the source of ozone is primarily outdoors, the indoor levels track the outdoor concentrations. Hence, in urban areas a strong diurnal variation is evident in indoor ozone concentrations, especially from early spring through late fall. Although the ozone concentrations decrease during wintertime, indoor ozone concentrations can still be large enough to promote indoor chemistry. In the presence of ozone, VOCs with unsaturated carbon-carbon bonds (*e.g.,* d-limonene, α-pinene, and α-terpinene) can react to form potentially irritating species that affect both people and equipment. Such species include organic acids and free radicals (Weschler and Shields, 1996; 1997). The latter species (*e.g.,* hydroxyl and hydroperoxy radicals) are extremely reactive and may contribute to corrosion processes.

Indoor ozone levels can be reduced by decreasing ventilation rates during periods when outdoor ozone levels are the highest. Ozone is readily removed from the ventilation air through the use of filters containing activated charcoal or chemically treated media (Weschler, Shields, and Naik, 1994; and references therein).

Guidelines

A set of HVAC guidelines for digital switch environments have been developed based on numerous studies by ourselves and others over the past two decades. Similar guidelines are likely to prove cost-effective in most commercial space that contains a large amount of electronic equipment.

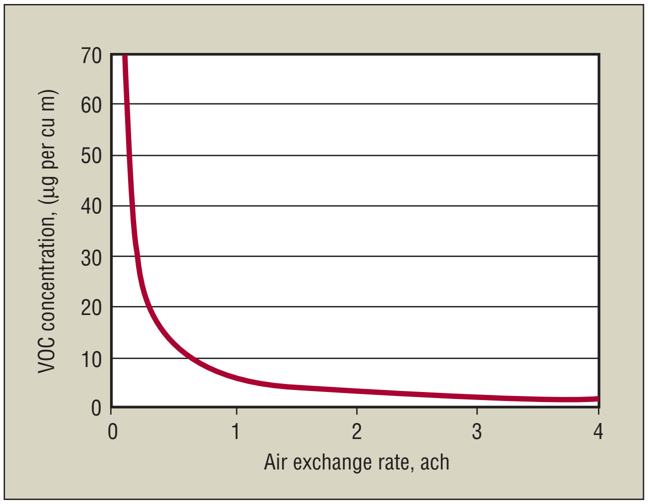
Table 5 presents a summary of these guidelines.

The rationale supporting each of these recommendations will be briefly discussed below.

- Minimum OA of ¼air change per hour (ach)-For pollutants with indoor sources, the pollutant concentration increases as the outdoor air fraction of the HVAC supply air decreases. (In the following discussion, ventilation refers to that portion of supply air that is outdoor air.) Indoor pollution sources tend to be especially important for VOCs. Certain acidic gases (*e.g.*, hydrogen chloride and nitric acid) can also have indoor sources. Fig. 2 illustrates the rapid increase in the concentration of a hypothetical VOC that may occur when the ventilation rate is reduced. (The figure shows equilibrium concentrations at different air exchange rates. The reader should appreciate that as the air exchange rate decreases more time is required to reach equilibrium in an indoor setting.)

In Fig. 2, the *Y*-axis denotes concentration (µg per cu m) and the *X*-axis denotes ventilation rate in ach. For the conditions modeled, the concentration of the VOC does not start to increase dramatically until the air exchange rate is less than about 0.5 ach. The air exchange rate at which this rapid increase begins will vary with the magnitude of the source strength-the greater the rate at which a VOC is emitted, the larger air exchange rate is needed to prevent this rapid increase. Hence, when pollutant source strengths are large (*e.g.*, when floors are waxed, when painting occurs, when new equipment is installed, etc.), the ventilation rate should be increased.

2 The effect of ventilation on the indoor concentration of a VOC with predominantly indoor sources (data are modeled results).



For daily activities in our telecommunications facilities, we find that ¼ ach is sufficient to prevent excessive buildup of VOCs and other pollutants with indoor sources. It should also be noted that local building codes will often include ventilation requirements that exceed this recommendation.

Recent studies in our laboratory have revealed that adequate ventilation is necessary not only to remove pollutants with indoor sources but also to limit reactions among indoor pollutants (Weschler and Shields, 1997b). At low ventilation rates, more time is available for indoor pollutants to react with one another. Such reactions are undesirable because some of the products are more reactive and corrosive than their precursors. This is especially true for reactions that produce free radicals.

Ventilation is essential to prevent equipment failures caused by pollutants with indoor sources. However, ventilation potentially increases the indoor concentrations of pollutants such as fine particles and ozone that have primarily outdoor sources. Fine particles can be removed from the ventilation air with proper filtration (as can ozone). This leads to the second guideline in Table 5.

- *Use higher efficiency filters*—The major source of fine particles in telecommunications facilities is the outdoor air used for ventilation, free air cooling (economizer operation), or building pressurization. This reflects the fact that these buildings tend to be free of combustion processes that might generate fine particles indoors, smoking and cooking are prohibited, and there are no gas-fired appliances.

Fortunately, the concentration of fine airborne particles within the facility can be adequately controlled with proper filtration. The emphasis in the previous sentence is on "proper." Fig. 3 demonstrates the difference in the concentration of airborne particles when filters having an ASHRAE dust spot rating of 85 percent are used in place of filters rated at 30 percent. This data is from two telecommunications facilities located in Phoenix, Ariz. The measurements were made at the identical time, and the concentration of particles in the outdoor air was comparable at both locations.

The first set of data shows the particle counts in seven size ranges for the office using 85 percent fil-

TABLE 5—HVAC guidelines for digital switch environments.

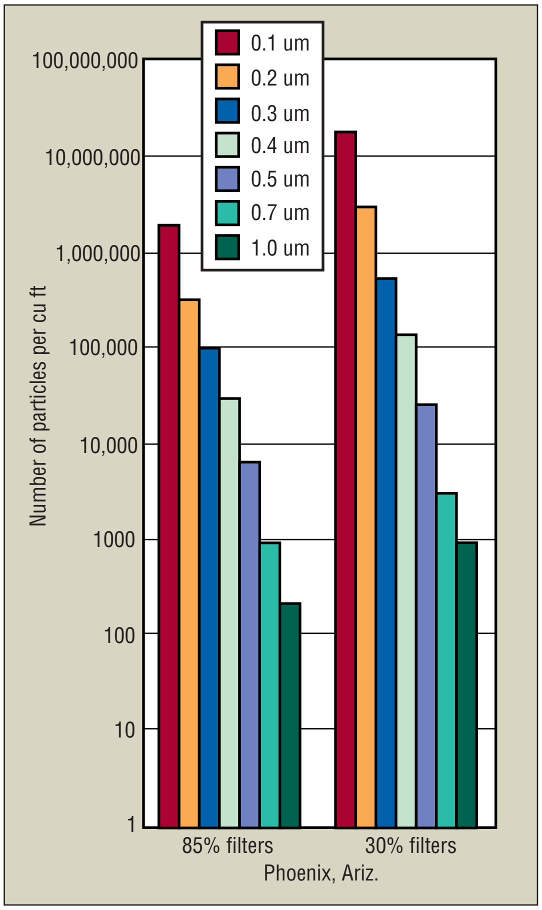
- ■ **The ventilation rate** (with outdoor air) should be, at a minimum 1/4 air change per hr.
- ■ **The filters used in the HVAC system** should have an ASHRAE dust spot rating of 85 percent or better.
- ■ **The pressure within the digital switch area** should be slightly positive with respect to the external environment (approximately 0.012 in. WG).
- ■ **The HVAC fans** should operate continuously.

ters in the HVAC system. The second set of analogous data is for the office using 30 percent filters. Note that the *Y*-axis is scaled logarithmically. In each size range, the particle concentration is 5 to 10 times larger in the office with the less efficient filters. Fig. 3 is just one “snapshot” from a more extensive study conducted in four different cities. However, it is representative of the overall results.

In essence, the need for filtration is driven by the fact that fine particles are responsible for most of the failures in modern electronic equipment. Filters with a relatively high ASHRAE dust spot rating are required to remove fine particles effectively.

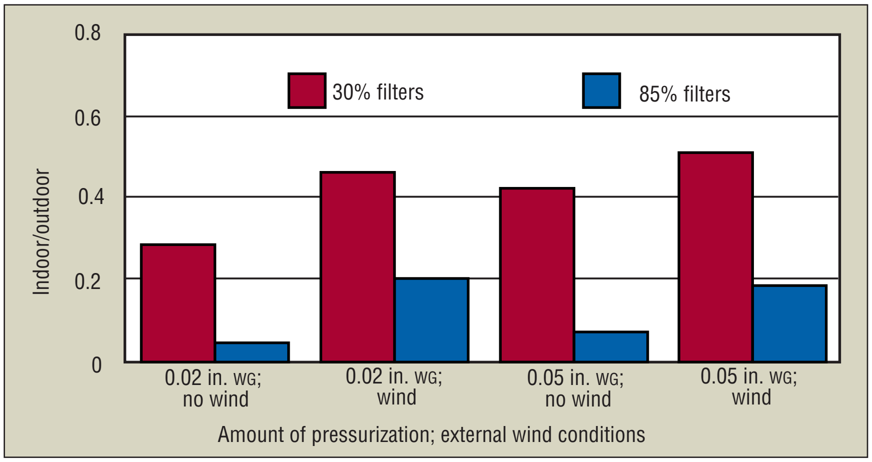
- *Slightly positive pressure*—The guideline for positive pressurization in digital switch areas was originally developed to reduce infiltration of outdoor air. Air that infiltrates normally has bypassed the HVAC system, including the measures designed to remove particles and control relative humidity and temperature. The more air that leaks into a building, the less control one has over the indoor environment. However, recent studies by M. K. Herrlin of Bellcore (Herrlin, 1997) have demonstrated that in terms of indoor levels of fine particles positive pressurization is normally counter productive.

To maintain positive pressure, additional outdoor air must be intentionally brought into a building (compared to a building without positive pressure). The additional outdoor air carries with it fine particles that further challenge the filters. If the filters are inefficient at removing fine particles (through poor design, installation, or maintenance) and if the structure requires a significant amount of additional outdoor air to maintain positive pressure (to compensate for a leaking building shell), then many more particles will enter the building with the additional air used for pressurization than will be kept out of the building by pressurizing (sealing) leaks in the building shell. The situation is improved somewhat as the building is tightened and the filter efficiency is increased.



3 Particle concentrations in different size ranges at two telecommunications facilities in Phoenix, Ariz. (data are field measurements). The buildings were using either 85 or 30 percent filters. The measurements were made at the identical time; outdoor concentrations were comparable; and there were no major indoor sources of fine particles.

Fig. 4 illustrates these concepts for a prototypical telecommunications facility that is assumed to be leaky (4.5 ach at 0.20 in. WG). The *Y*-axis represents the indoor/outdoor (I/O) ratio for fine particles. The *X*-axis presents four scenarios: 0.02 in. wg internal pressurization and no wind blowing against the outside of the structure; 0.02 in. WG pressurization and an 18 mph wind blowing against the outside of the structure; 0.05 in. WG pressurization and no wind; and 0.05 in. WG pressurization and an 18 mph wind. The red bars show the I/O ratios for a building using 30 percent filters, and the blue bars are for a building using 85 percent filters. For conditions with “no wind,” as the pressurization increases from 0.02 to 0.05 in. WG., the I/O ratio for fine particles actually increases for buildings with both 30 and 85 per-



4 The effect of building pressurization on the indoor concentration of fine particles (data are modeled results). The *Y*-axis represents the indoor/outdoor ratio of fine particles; the *X*-axis presents four scenarios. The building is assumed to be using either 30 percent filters (red bars) or 85 percent filters (blue bars) and to be leaky (4.5 ach at 0.20 in. WG).

cent filters. When an 18 mph wind is blowing, as the pressurization increases from 0.02 to 0.05 in. WG, the I/O ratio increases for the building with 30 percent filters but decreases slightly for the facility with 85 percent filters. In addition to the increase in indoor fine particles that may result from pressurization, there is an energy penalty if the additional outdoor air has to be conditioned.

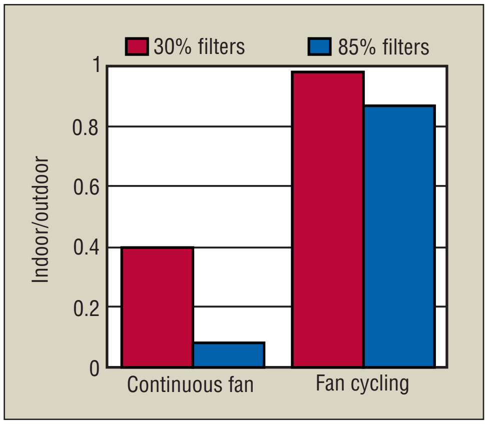
Although pressurization can be counterproductive, maintaining a slight but controlled positive pressure is preferable to a neutral indoor pressure. In the latter case, the building can unintentionally be put under negative pressure (*e.g.,* from exhaust fans with no makeup air supply) leading to the introduction of unconditioned air.

Engineers should also be aware of occasions when even a slight positive pressure should not be maintained. These include any situation where it is undesirable to introduce outdoor air. Examples include dust storms, forest fires, volcanic eruptions, and extreme smog events. For example, when Mount St. Helens exploded on May 18, 1980, a thick cloud of volcanic ash traveled over a vast area. There was sufficient time (up to 6 hours) to close outdoor air intakes and otherwise seal many downwind telephone switching centers-primarily to protect the electronic equipment and also to avoid fouling the outdoor air intakes and overwhelming the filters with particulate matter.

Additionally, for buildings with indoor sources of water vapor, it generally is not advisable to maintain positive pressure when outdoor temperatures are quite low. In such situations, as indoor air is forced out of the building shell, water may condense on cold structural surfaces leading to damage.

There are times when the I/O vapor pressure difference is such a significant factor that it can cause problems, for example sun-driven vapor diffusion through rain-wetted walls. Under such conditions, the vapor pressure would overwhelm any practical air pressure difference.

To help protect against moisture transport from air pressure and vapor pressure differences, a properly designed and installed vapor barrier is strongly recommended. If there is no vapor barrier or a vapor barrier's effectiveness is voided by improper installation or damage, moisture will enter the wall cavity and condense when it reaches the dew point.



5 The effect of fan cycling on the indoor concentration of fine particles (data are field measurements). The *Y*-axis represents the indoor/outdoor ratio of fine particles; the *X*-axis presents two scenarios (continuous fan operation and fan cycling. The buildings were using either 30 percent filters (red bars) or 85 percent filters (blue bars).

- *Continuous HVAC fan operation*—Fig. 5 summarizes results of fan-cycling studies conducted at telecommunications facilities located in Wichita, Kans,. and Lubbock, Tex. (Weschler, Kelty, and Lingousky, 1983). The former facility was equipped with 30 percent filters while the latter facility had 85 percent filters. During periods of fan cycling at the office with 30 percent filters, the ratio of indoor to outdoor fine particle concentrations was 2.5 times larger than during continuous fan operation. At the office with 85 percent filters, the ratio of indoor to outdoor fine particle concentrations was 10 times larger during periods of fan cycling. The observed increases in fine particle concentrations during fan cycling were due primarily to a lack of constant filtration. Consequently, the office with more efficient filters displayed the largest increase in fine particle concentrations when the building fans were cycled.

Consider the first three guidelines in Table 5. If the HVAC fans are not operating, each of these recommendations is compromised: there is no mechanical ventilation, no air is being passed through the building filters with subsequent particle removal, and the pressure of the equipment space is neutral or negative with respect to the external environment. As HVAC fans are cycled on and off, there is also an increased likelihood that building filters will dump some of their captured particles. This is especially true if the filters are overloaded. Finally, when fans are off, "hot spots" can develop in certain pieces of equipment; when the fans come back on, there is a possibility of thermal shock. When the fans operate continuously, the probability of thermal shock within a piece of electronic equipment is greatly reduced.

Conclusions

The guidelines presented in Table 5 will increase the costs associated with operating a building. However, they will also reduce the likelihood that electronic equipment housed within a building will fail as a consequence of environmental factors. Cost/benefit studies for telecommunication facilities indicate that benefits derived from these guidelines outweigh their cost (Weschler, 1990).

In the case of large office buildings that house both people and electronic equipment (personal computers and related peripherals), the guidelines presented in Table 5 may be even more cost-effective than in telecommunication facilities. In such facilities, the guidelines benefit both the equipment and the personnel. Indeed, a recent study (Fisk and Rosenfeld, 1997) suggests that in terms of improved worker productivity and health the benefits derived from improving indoor environments exceed the costs by a factor of 18 to 47. The accrued benefits are even greater if reductions in costly electronic failures are taken into account. **HPAC**

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