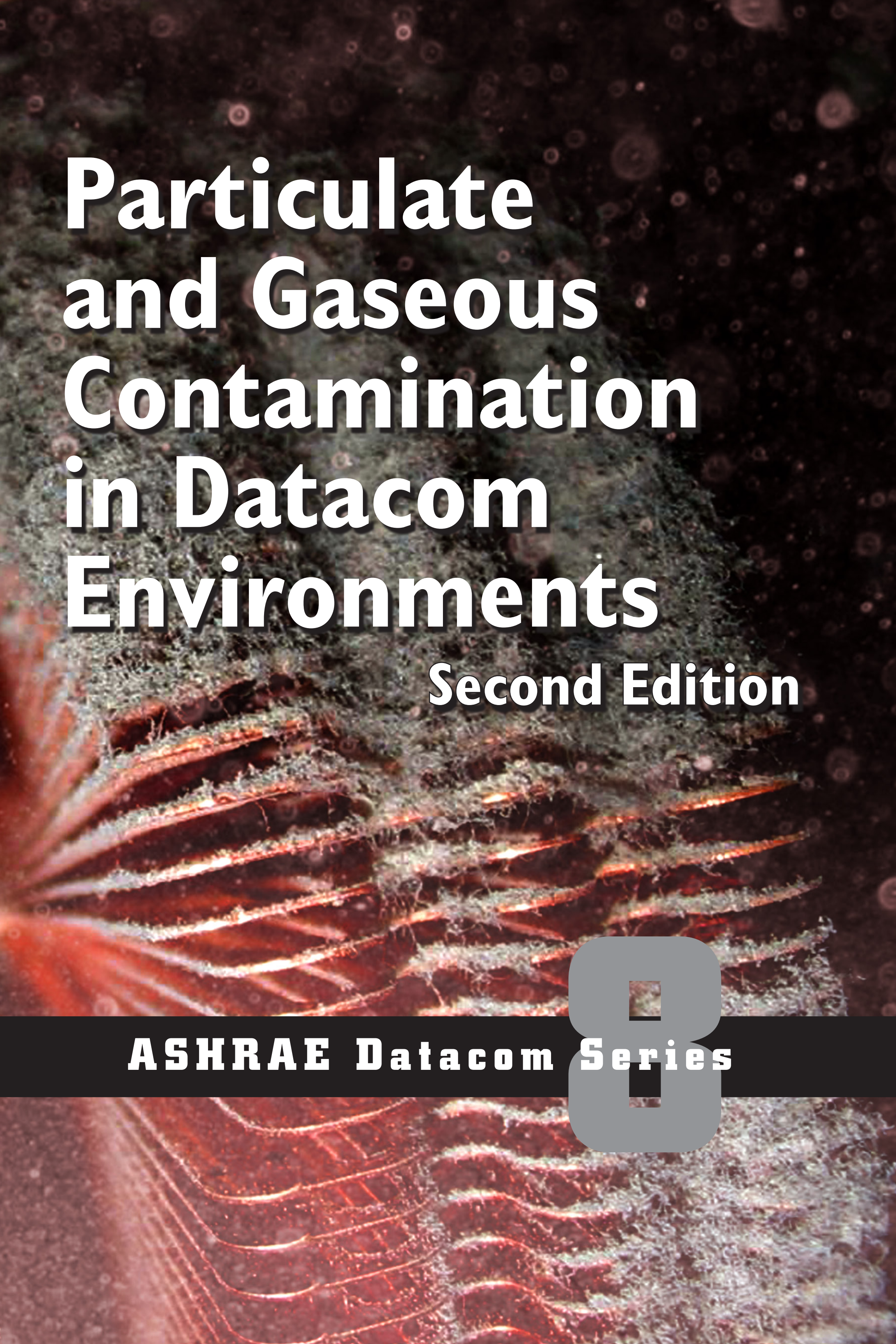

Particulate and Gaseous Contamination in Datacom Environments

Second Edition

ASHRAE Datacom Series

8

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Second Edition

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Second Edition

ASHRAE Datacom Series
Book 8

ASHRAE
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Preface

The first edition of *Particulate and Gaseous Contamination in Datacom Environments* provided comprehensive coverage of monitoring, preventing, and controlling particulate and gaseous contamination in data centers. It was published as a result of the of increased information technology (IT) and datacom equipment failure rates in the mid-2000s. The increased failure rates resulted from multiple factors, including product design and manufacturing process changes to comply with the European Union Restriction of Hazardous Substances (RoHS) directive, expansion of installations in Asian geographies with high levels of environmental sulfur-bearing gaseous pollution, and the ever-increasing electronic component packaging density with resulting finer-pitch interconnect spacing. Higher packaging density does not always allow the hermetic sealing of components, further exposing the electronics to the detrimental effects of moisture and particulate and gaseous contamination. The first edition emphasized the need for datacom facility designers and operators to expand their thinking beyond just the physical infrastructure of the data center by including the additional reliability threat to datacom equipment from particulate and gaseous contaminations, especially when located in polluted urban environments.

Since the first edition, significant progress has been made in being able to predict corrosion-related hardware failures that result from gaseous contamination in the air and the deliquescence relative humidity of the dust particles. This progress was a key reason for publishing the second edition. The description of dust particle corrosivity and its relationship with deliquescent relative humidity in promoting corrosion and/or ion migration on IT and datacom equipment has been expanded. Chapter 4, which describes gaseous contamination monitoring, was expanded to include details on the reactive monitoring method using coulometric reduction. Another addition to the second edition is the ASHRAE data center survey results that led to the conclusion that silver is a much better predictor of corrosion-related hardware failures. The original chapter on prevention and control in the first edition was split into two chapters so as to describe each topic in greater detail and to allow the information presented to be more applicable to real-world situations and useful to data center designers and operators. Every chapter in the second edition has been updated.

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1

Introduction

Data center owners and operators focus much of their attention on the physical infrastructure related to electrical power, cooling, and humidity control. However, today's intricate and sensitive IT equipment and the related communications networks, also called *datacom equipment* or *computer equipment* throughout the book, require a certain level of environmental control of particulate and gaseous contaminations. Datacom equipment center environmental contaminations are often overlooked and, if left unrestrained, can degrade the reliability of mission-critical IT and datacom equipment.

Environment-related IT and datacom equipment failures generally require three necessary conditions to be satisfied: (1) environment is contaminated with corrosive particles and/or gases, (2) the relative humidity is high, and (3) the hardware, by design or by manufacturing processes, is susceptible to failure due to corrosive particles and/or gases. Removal of any of these three necessary conditions generally eliminates the corrosion mechanisms. An exception is the corrosion of silver, which can occur at low humidity levels. Temperature is another factor that affects corrosion. The first necessary condition of contaminated environment is satisfied especially in the Asia-Pacific region (except Australia), which has experienced a proliferation of IT and datacom equipment centers with the ever-rising levels of pollution associated with industrial development that relies heavily on fossil fuels for its growing energy needs. The second necessary condition is satisfied by the continuous expansion of the temperature-humidity envelope to improve performance and reduce cost. Every design change, however minor and thoroughly qualified, has the possibility of exposing hardware to corrosion susceptibility. The biggest design change in recent years resulted from the requirement to comply with the European Union directive 2002/95/EC of the European Parliament and of the Council of 27 January 2003 on the restriction of the use of certain hazardous substances in electrical and electronic equipment (RoHS 2003). The directive, commonly known as RoHS, was implemented in July 2006. It restricts the use of six hazardous substances in electrical and electronic equipment. The restriction on the use of lead metal, used mostly in lead-tin solder, has had the most dramatic impact on IT equipment reliability. It has taken time and effort to reduce the negative impact of the change to lead-free solder alloys. Given that IT equipment designers will keep pushing the technology envelope, which will sometimes make the hardware susceptible to the corrosive particles and gases in the environment, it is incumbent on the datacom equipment center owners to protect their IT and datacom equipment by taking reasonable actions to reduce the concentrations of corrosive particles and gases.

To maintain a high level of IT equipment reliability, it is important to view contamination in a holistic way. It should be acknowledged that the datacom equipment center is a dynamic environment where maintenance operations, infrastructure upgrades, and IT equipment change activities occur on a regular basis. Airborne contaminants harmful to sensitive electronic devices can be introduced into the operating environment in many ways during these and other activities. The fundamental focus areas that necessitate examination start with the outdoor air pollutants surrounding the facility. Outdoor air that enters the building, as a result of free-air cooling or pressurization of the datacom equipment center, or air exchanges from leaks in the facility envelope or human occupancy, must be filtered and possibly conditioned. Contamination from construction and, maintenance operations within the building's environmental envelope and from the data center infrastructure equipment itself must be considered. Data center workers also contaminate the datacom equipment center from hair, lint on clothing, and outdoor contaminants tracked in on footwear. With proper planning and controls, contamination and its negative effects can be minimized.

Datacom managers and operators should include environmental contamination monitoring, prevention, and control as a part of the standard operating procedure. The association between contamination and hardware failures should not be overlooked. Occasionally, the absence of contamination controls results from cost-cutting actions or from lack of appreciation of the detrimental effects of contamination. Particulate and gaseous contamination can cause intermittent equipment glitches or unplanned shutdowns of critical systems, resulting in significant business and financial losses. Examples of contamination events and their effects on hardware reliability are provided throughout the book.

The intent of this publication is to provide information that is essential to the monitoring, prevention, and control of particulate and gaseous contamination within datacom facilities. Understanding the critical parameters outlined in this publication will provide equipment manufacturers and facilities operations personnel a common set of guidelines for contamination monitoring, prevention, and control that can enhance datacom equipment reliability. The book does not cover issues related to contamination and filtration of open water systems, such as condenser water systems, used in datacom environments.

The intended audience for this publication includes

- datacom facility operation managers,
- datacom facility architects and engineers who require insight on datacom environmental controls for gaseous and particulate contamination,

- datacom facility support infrastructure service providers,
- datacom facility planners, and
- datacom equipment manufacturers.

1.1 GASEOUS CONTAMINATION

Gaseous contamination refers to gases such as hydrogen sulfide, sulfur dioxide, oxides of nitrogen, carbon dioxide, chlorine, and ozone that can have adverse effects on computer hardware. The harmful gases are by-products of geological, biological, agricultural, industrial, and manufacturing activities. They can, even in the low ppb (parts per billion [10^9]) levels, act alone or in synergy with each other or particulate matter to corrode metallic materials, causing irreversible damage to circuit boards, connectors, integrated circuits, and various other electronic components.

1.1.1 Gaseous Contamination Sources

Gaseous contamination sources are many. Some of the common gases, their origins, and their corrosive effects are listed here.

Hydrogen sulfide, the gas generally the most corrosive to electronic hardware, is a by-product of fossil fuel processing and combustion, wood pulping, sewage treatment, ore smelting, and sulfuric acid manufacturing (ISA 1985, Muller 1991). Geothermal emissions often contain hydrogen sulfide. Human settlements with high density and poor-to-nonexistent sanitary facilities are often high in hydrogen sulfide pollution. Landfills are notorious for giving off hydrogen sulfide. Office and industrial complexes built on landfills have been known to suffer from hydrogen sulfide pollution for many years (Sahu 2007).

The main sources of sulfur dioxide emission include power plants, industry, and to a lesser extent transportation (Lu et al. 2010). Power plants exhaust sulfur dioxide by burning low-grade coal. The industrial sources include paper mills and oil refineries. While sulfur dioxide is known to react with water forming sulfuric acid, an acid very corrosive to metals, sulfur dioxide is not a corrosion concern in IT equipment housed indoors (Abbott 1987).

Chlorine gas by itself is not very corrosive to copper or silver but has a strong synergistic effect on the corrosion of these metals by hydrogen sulfide (Muller 1991). It is given off by common household cleaning chemicals. It is also emitted by aluminum manufacturing, paper mills and garbage, by the burning of fossil fuels, and by water treatment plants and insecticides (Rice 1980).

Hydrogen chloride gas can dissolve in water, forming hydrochloric acid, which can attack metals such as copper and silver, forming copper and silver chlorides. Hydrogen chloride gas is a by-product of waste incineration. It is also given off by automobile emissions, oceanic processes, and polymer combustion (ISA 2013).

Nitrogen dioxide is a highly reactive gas, forming acid with water, which can corrode electronic hardware. It can also act in synergy with hydrogen sulfide to hasten the corrosive attack of metals (Muller 1991). It is found in automobile emissions and is given off by fossil fuel combustion, microbes, and the chemical industry (ISA 2013).

Ozone is produced by natural and anthropogenic electrical discharge. Ozone enhances the corrosion of copper and silver. According to Rice (1981), ozone oxidizes hydrogen sulfide to form sulfur, which reacts readily with silver.

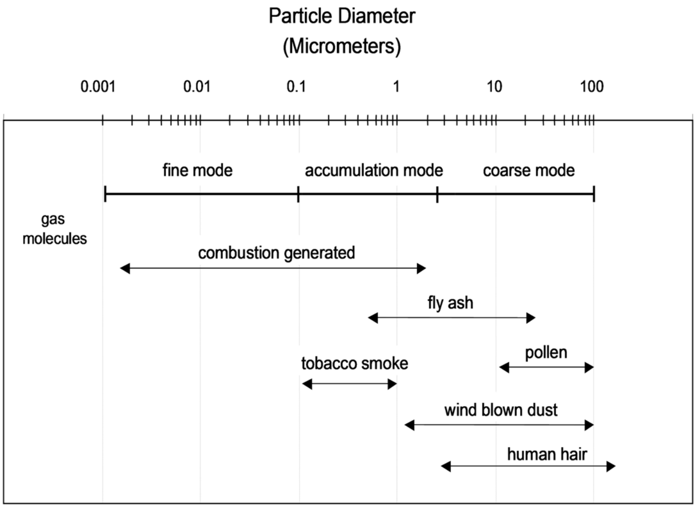
1.2 PARTICULATE MATTER

Particulate matter refers to airborne solid and liquid particles. For the purposes of this book, the terms particle, particulate, aerosol, and dust will be considered equivalent and all are represented by the term particulate matter. The size of particulate matter spans a vast range from about 0.001 to more than 100 μm. The United States Environmental Protection Agency (EPA), which monitors particulate matter from a health point of view, categorizes particle mass concentration as $PM_{2.5}$ and PM_{10}, representing particles smaller than 2.5 and 10 μm, respectively. Particulate matter may also be categorized in three size modes: fine mode (0.001 to 0.1 μm), accumulation mode (0.1 to 2.5 μm), and coarse mode (2.5 to 10 μm). The coarse mode is generally limited to particles smaller than 10 μm but can include much larger airborne fibers and particles. Particulate matter in each of these size categories may be composed of various materials from many different sources. Figure 1.1 illustrates the typical size ranges of particulate matter (Bell 2000). Particles smaller than 0.1 μm are large in number density but have small mass per unit volume of air. Therefore, in this book, we will redefine fine particles as having size less than 2.5 μm. Another reason for this size redefinition is to align the definition of fine particles to that of the USA EPA (EPA 2013) and to that of many recent research works on the effect of fine particles on datacom equipment corrosion and reliability (Litvak et al. 2000, Burnett et al. 1992). Coarse particle definition will remain unchanged as having size larger than 2.5 μm. Throughout this book, fine particles will refer to particles smaller than 2.5 μm and coarse particles will refer to particles larger than 2.5 μm.

1.2.1 Particulate Matter Sources

Particulate matter is generated both naturally and by humans (anthropogenically).

Fine particles (<2.5 μm), such as those found in smoke and haze, are of two types: primary and secondary (EPA 2013). The primary fine particles are directly emitted from a source, such as a forest fire, volcanoes, construction sites, unpaved roads, fields, or smokestacks. The secondary fine particles, which make up most of the fine particulate pollution, form in complicated photochemical reactions, in the atmosphere, from chemicals such a sulfur dioxide and nitrogen oxides that are emitted from power plants, industries, and automobiles. The sulfur dioxide and nitrogen dioxide, along with carbonaceous material seed particles (<0.1 μm), interact in a complex, multistep photochemical process to produce sulfuric and nitric acids.



I-P conversions:

$0.001\ \mu\text{m} = 3.94 \times 10^{-8}$ in.

$0.01\ \mu\text{m} = 3.94 \times 10^{-7}$ in.

$0.1\ \mu\text{m} = 3.94 \times 10^{-6}$ in.

$1\ \mu\text{m} = 3.94 \times 10^{-5}$ in.

$10\ \mu\text{m} = 3.94 \times 10^{-4}$ in.

$100\ \mu\text{m} = 3.94 \times 10^{-3}$ in.

Figure 1.1 Size ranges of various PM sources (Bell 2000).

These acids are neutralized by ammonia from fertilization, decay of biological materials, and other sources to product fine particles dominated by ammonium sulfate, ammonium hydrogen sulfate, and ammonium nitrate. The majority of these secondary fine particles would be considered anthropogenic (Litvak et al. 2000, Comizzoli et al. 1993, Seinfeld and Pandis 1998).

Coarse particles (>2.5 µm) can include sea salt, natural and artificial fibers, plant pollens, and wind-blown dust. Their sources include erosion of soil and minerals and flaking of biological materials. (Comizzoli et al. 1993).

Conventional filters in mechanical ventilation systems are able to very efficiently remove particulate matter in the coarse size range (>2.5 µm). Figure 1.2 shows the minimum efficiency reporting valves (MERVs) of MERV 9 and MERV 13 filters as a function of particle size (Hanley et al. 1994, Riley et al. 2002). Coarse particles are effectively filtered by the mechanism of inertial impaction, interception and by the straight forward sieving of particles when their diameter is greater than the pore size of the filter. Impaction occurs when a large, heavy particle is unable to follow the airflow streamline and bypass the filter fiber. Interception is a particle separation process where the particle in the air is intercepted by the filter fiber. Interception occurs due to the distortion of the flow field around a fiber due the proximity of other fibers.

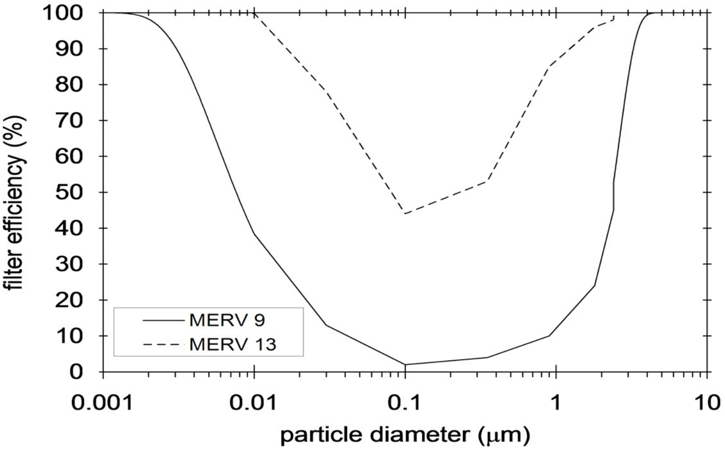


Figure 1.2 Filter efficiency of commonly used filters in datacom environments (Hanley et al. 1994; Riley et al 2002).

Particles smaller than 0.1 μm have high filtration efficiency because of diffusion. Smaller particles diffuse to the filter fibers and are collected more rapidly than larger ones.

Particles in the intermediate size range (roughly 0.01 to 2.5 μm) are most difficult to remove, because these particles easily follow the airflow through the filter fibers compared to larger particles and they have lower ability to diffuse compared to the smaller particles.

Outdoor particles larger than 2.5 μm (coarse particles) can be readily captured by conventional filters and thus prevented from entering datacom equipment centers. But these coarse particles can bypass poorly fitted filters and can enter data centers through openings in the building envelope. Datacom equipment centers can be positively pressurized to avoid this form of particle infiltration. However, one study indicates that the introduction of outdoor air for the sole purpose of guarding against infiltration actually carries more particles into the building than the added pressure keeps out (Herrlin 1997). A more recent study by a team at the Lawrence Berkeley National Laboratory, however, indicates that improved filtration of incoming air could reduce the particle contamination in a data center (Shehabi et al. 2010).

Measurements have shown outdoor air to be the main source of particulate matter in the data center environment (Shehabi et al. 2008), but anecdotal evidence suggests that episodic indoor events can also potentially contribute to indoor particulate matter concentrations. Indoor-generated particulate matter can include particles in all size ranges. Fan belt wear in air-handling units (AHUs), toner dust from copiers, and printers can be sources of coarse particles. Coarse particles can also come from occupant hair and clothing or occupant activities, such as the unpacking of equipment. Construction activities can generate contamination such as cement dust, drywall dust and insulation, paper, and cardboard fibers. Fibers from occupants or occupant activities consisting of particles larger than 10 µm can be of concern. Other documented fibers include small zinc formations, commonly referred to as *zinc whiskers*, which have been observed forming on the surfaces of zinc electroplated steel (Lahtinen and Gustafsson 2005).

The presence of high levels of outdoor particulate matter is often associated with high levels of gaseous contamination, particularly in emerging economies, since both these contaminants are a by-product of industrial activity in regions where environmental controls are not strictly enforced.

Fine particles (<2.5 µm) are the particulate matter of principal concern in datacom equipment centers with well-filtered air for two reasons: (1) as described above, fine particle filtration is not efficient, and (2) fine particles are very corrosive and have high concentrations of ammonium salts. Coarse particles, on the other hand, are generally quite inert, with the exception of sea salt. Under extreme, though rare, conditions of very high levels of contamination, coarse particles and fibers can plug heat sinks and degrade connector reliability.

1.2.2 Particulate Matter Transport in a Datacom Equipment Center

Particulate matter is transported with the movement of air, also known as *advection*, throughout the datacom equipment center. Computer room air-conditioning (CRAC) units, also called computer room air-handling (CRAH) units, often provide air conditioning in datacom equipment centers. Air enters the CRAC/CRAH units at the top and the conditioned air exits at the bottom. Datacom equipment centers can be raised-access floor or non-raised-access floor environments. Figure 1.3 shows the airflow in a typical raised-access floor data center. Outdoor air, also referred to as *makeup air*, enters the air-handling unit (AHU), where it passes through a series of filters and may be conditioned before it enters the data center. The conditioned air is then forced in to the space under the raised floor by the CRAC/CRAH units to flood the cold aisles of the data center where the air enters the front faces of the computer racks, also referred to as *servers*. Fans within the datacom equipment (servers) pull air through the racks, forcing the warmed air into the hot aisles and eventually back into the intakes at the top of the CRAC/CRAH units. Most air recirculates in the datacom center. The majority of datacom centers are designed to have only a small portion of outdoor air enter the datacom center for positive pressurization and/or fresh, makeup air necessary for human occupancy. Some datacom centers provide no ductwork for outdoor air to directly enter the datacom center. Rather, outdoor air is only provided by infiltration from adjacent zones, such as office spaces or hallways. However, a growing number of datacom centers have been using air handlers designed with air-side economizers (similar to those used in

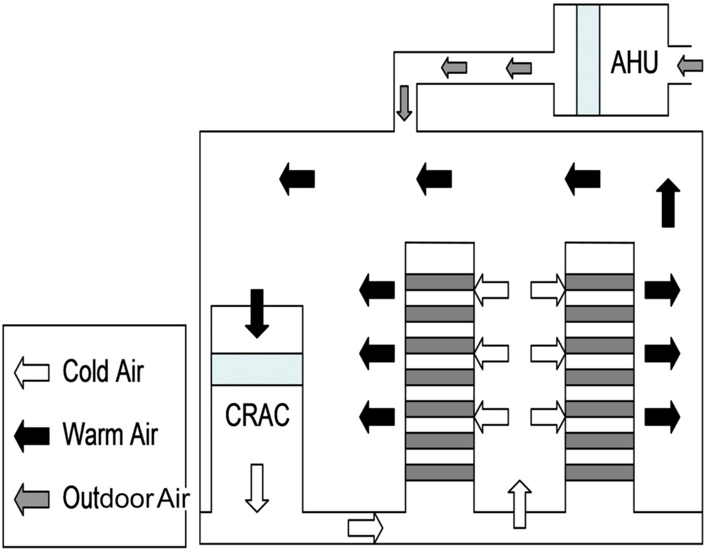


Figure 1.3 Airflow in a raised-access floor data center.

commercial buildings) to take advantage of the energy-efficiency benefit of using a high volume of outdoor air for cooling the datacom equipment. It should be noted that the traditional closed-flow layout results in the same air circulating through the filters repeatedly. In case of datacom centers with well-designed air-side economizers, the majority of air filtration is done before the air enters the datacom center.

1.2.3 Mechanism of Particulate Matter Settling

Particulate matter deviates from airflow paths and settles onto interior surfaces primarily through three mechanisms:

- Gravitational settling
- Diffusional movement
- Electrostatic attraction

Gravitational settling is a function of particle mass and has the greatest influence on large particles. Gravitational settling becomes insignificant for particles smaller than approximately 1 μm (in diameter), while particles greater than 10 μm have short airborne residence times due to the strong gravitation forces that cause particles to quickly settle onto horizontal surfaces. Strong air currents can prolong airborne residence times, even for large particles.

The diffusional movement of particulate matter is caused by the random collision of air molecules against airborne particles. The result of these collisions allows particles to migrate from higher particle concentrations to lower particle concentrations. Diffusion is significant only with very small particles and has minimal influence on particles larger than 0.1 μm in diameter. Diffusion affects particles equally in all directions. While larger particles primarily deposit onto horizontal surfaces, smaller particles have an equal tendency to deposit on both horizontal and vertical surfaces.

Electrostatic attraction is the force between opposite charges that pulls particles together. It causes them to settle on surfaces. An example of electrostatic attraction are the forces that cause synthetic-fabric clothes to cling together.

Once a particle comes into contact with a surface, either by gravitational settling, diffusional movement, or electrostatic attraction, it is generally expected to remain deposited. Resuspension of particles in the air is expected to be minimal because of the cohesive forces between the particles and surface. Mechanical processes such as floor sweeping, movement of floor or ceiling tiles, or equipment maintenance often cause resuspension.

1.3 DIFFERENCES BETWEEN HUMAN HEALTH AND DATACOM EQUIPMENT CONCERNS

Humans and computers are both vulnerable to particulate matter, especially to fine particles ($PM_{2.5}$), though the nature of vulnerabilities differ. According to the United States EPA, fine particles are the main cause of reduced visibility, referred to as *haze* in the daily weather reports. They readily enter the lungs, being too small to be filtered in the nose and the throat. There is a strong evidence that $PM_{2.5}$ particles can cause heart and lung health effects, though researchers are still grappling with what makes fine particles toxic. Some suspect that it is the size that determines toxicity. Yet, other studies that followed people over many years show a clear association of sulfates in $PM_{2.5}$ with health effects (Kaiser 2005).

$PM_{2.5}$ particles are chemically more harmful to computers because of their higher ionic content, whereas, coarse particles (>2.5 μm) are more harmful from a mechanical point of view, such as interruption of airflow in heat sinks or the interruption of electrical signals through electrical connectors.

Datacom equipment centers are often required by country or local codes to have a certain minimum rate of makeup air entering the facility for reasons of human health. For example, the China National Standard GB 50174-2008 requires 40 m^3/h (23.5 cfm) of fresh makeup air for each person in a data center (China Electronics Engineering Design Institute 2008). There is no such requirement for the reliable functioning of the datacom equipment.

1.4 OVERVIEW OF CHAPTERS

Chapter 1 describes the purpose and objective of the publication as well as provides background information on the importance, sources, and nature of particulate matter and gaseous contamination. A brief overview of the remaining chapters and their interrelations is also included.

Chapter 2 discusses particulate matter and gaseous contaminants and how their interaction can impact the reliable operation of datacom equipment. The chapter examines the datacom equipment components, devices, and subsystems vulnerable to particulate and gaseous contaminants and describes their mechanical, chemical, and electrical effects, such as overheating, corrosion, and arcing that can degrade the reliability of the datacom equipment.

Chapter 3 deals with several test methods, guidelines, and limits available for consideration and use in datacom environments. This chapter examines pertinent documents but does not recommend a single set of limits. Because of the complexity of particulate matter and gaseous impacts on datacom equipment, individual datacom manufacturers may choose to either adopt a single industry work, adopt a combination of industry works, or establish their own set of design requirements. Establishing individual test methods and limits is done to address specific materials, electrical design characteristics, and/or thermal design characteristics necessary to meet performance or other critical design objectives.

Chapter 4 covers the monitoring of particulate matter and gaseous contamination. Besides the concentration of airborne particles in terms of $\mu g/m^3$ or counts/m^3, the deliquescent relative humidity of the particulate matter is emphasized as a measure of the corrosivity of dust. The chapter explains that detrimental effects of gaseous contamination are better measured using reactive monitoring than by relying on the actual concentrations of the gaseous contaminants. The result of a landmark ASHRAE survey of datacom centers is presented that proved that silver corrosion rate is a better predictor of IT and datacom equipment corrosion-related failures than copper corrosion rate, as was previously, generally believed.

Chapter 5 describes the best practices for facility-level prevention of particulate matter and gaseous contamination. The particulate matter and gaseous contamination exposure risks and hazards must be identified so that datacom equipment centers can be designed and constructed to keep contamination out. Contaminant prevention is a very important consideration with respect to facility location, design, construction, and the cooling system.

Chapter 6 describes the best practices for facility-level control of particulate matter and gaseous contamination. Even with contamination mitigation through prevention, potential particulate matter and gaseous contamination sources are unavoidable and must be controlled. Actionable recommendations aimed at controlling contamination are provided in this chapter to be incorporated into general business processes and procedures.

Chapter 7 deals with the subject of air-side economizers, which represents a significant opportunity for datacom equipment centers to save energy. The chapter offers a set of considerations for implementing air-side economizers successfully. It also identifies potential threats to datacom equipment centers.

Chapter 8 offers a short summary of the key ideas presented in this book.

Appendix A describes coulometric reduction method for measuring the air corrosivity level in data centers.

Appendix B describes the relationship of the copper and silver corrosion rates reported in terms of rate of mass gain (μg) per unit area (cm^2) per unit time (h) to the rate of change of corrosion product thickness (ångströms per month).

Appendix C gives examples of case studies illustrating the impact of contamination on the operation of the datacom equipment center.

The Glossary of Terms lists the common terms used in the book.

2

IT and Datacom Equipment Vulnerability

Particulate and gaseous contaminations are present to varying degrees in all datacom equipment center environments. In a well-provisioned facility with a properly maintained filtration system, the concentrations of contaminants should generally pose little to no threat to the IT and datacom equipment. However, when considering typical datacom equipment center environments, there may be reasons for equipment vulnerability concerns. Even properly filtered datacom equipment center environments may contain particulate matter, however low in concentration, that may be harmful to the equipment. Gaseous contamination, in high enough concentration, with potential to damage datacom equipment, may also be present. The potential for adverse effects is increased when contaminants and particulate contaminants combine synergistically and high humidity levels exist. Under these circumstances, even relatively low concentrations of contaminants can cause intermittent malfunctions, undesirable changes in electrical characteristics, or complete equipment failure.

Some regions of the world pose greater risks because of higher levels of particulate and gaseous contamination in outdoor environments. Increased risks also arise from poor facility design practices and operational methods and from the proliferation of datacom equipment centers into more polluted geographies.

This chapter examines how datacom equipment may be vulnerable to airborne particulate and gaseous contaminants. The chapter emphasizes the need for a well-maintained datacom equipment center environment in which the contaminant levels are monitored and controlled to below the acceptable limits.

2.1 REASONS FOR INCREASED CONCERN

Continuing trends towards miniaturization of components and features in IT and datacom equipment make airborne contamination a more significant concern than it has been in the past. Higher power densities within air-cooled equipment require more efficient heat sinks and greater airflow velocities, resulting in increased exposure to airborne contaminants. Some modern high-density cooling systems are highly efficient when clean but may readily clog with airborne particulate matter over time, resulting in the degradation of their cooling efficiencies. Particulate matter can also degrade the high-density electronic interconnects that require tighter control of their electrical impedances. Narrow electronic component terminal spacing also increases the possibility of electrically conductive bridging by settled particulate matter.

2.1.1 Restriction of Hazardous Substances

Directive 2002/95/EC of the European Parliament and of the Council of 27 January 2003 on the Restriction of the use of Certain Hazardous Substances (RoHS) on Electrical and Electronic Equipment restricts the use of lead in electronic equipment, requiring manufacturers to redesign their IT and datacom equipment and change their manufacturing processes (RoHS 2003). Some of the design and process changes have made the equipment more vulnerable to gaseous and particulate contamination. For example, creep corrosion has been experienced on lead-free printed circuit boards (PCBs) in environments where lead-based soldered assemblies performed much more reliably. Recently, manufacturers of electronic equipment have characterized these failure mechanisms and are incorporating design rules, test methods, and modified surface finishes and soldering fluxes to improve equipment reliability (Schueller 2007, Fu et al. 2012a, 2012b).

2.2 PARTICULATE MATTER PROPERTIES AND EFFECTS

Particulate matter can be composed of organic, inorganic, synthetic, or metallic materials, alone or in combination, and can take various shapes: granular, fibrous, plate-shaped, or irregular. Particulate matter can be abrasive, corrosive, electrically and thermally conductive or insulative, and hygroscopic. It can interfere with airflow and optical signaling. Accumulation of particulate matter is also cosmetically undesirable. The wide range of potential contaminant characteristics makes it difficult for equipment designers to anticipate all the hazards particulate matter may pose.

The effects of particulate matter contamination on IT and datacom equipment can generally be categorized as follows:

- Mechanical effects include obstruction of cooling airflow, interference with moving parts, abrasion, optical interference, interconnect interference, or deformation of surfaces (e.g., magnetic media) and other similar effects.
- Chemical effects include corrosion of surfaces, ion migration resulting in metallic dendrite growth, and material property changes such as embrittlement or optical clouding of surfaces.
- Electrical effects include impedance changes and electronic circuit conductor bridging.

These particulate matter contamination effects may occur alone or in combination. Some effects may take place from only one form of airborne contamination, others may require combinations of contaminants.

In general, the amount of particulate matter accumulation is dependent on the volume of air flow per unit area through the equipment. For this reason, forced-air-cooled equipment may be more susceptible to particulate matter accumulation than liquid-cooled or free-convection-cooled equipment. Not all particulates entering equipment will be captured by the equipment, some particles will pass through and exit with the exhaust air.

Some areas within air-cooled equipment are more likely to collect particulate matter than others. The following are examples of typical accumulation locations:

- Small airflow openings, such as intake and exhaust vents, including unintended air leakage areas like rivet holes and sheet metal seams
- Fine-pitch heat sink cooling features
- Areas where flow bypass is not possible (particularly noticeable where flow ducting is used to force air through a heat sink)
- Areas where airflow undergoes a sudden reduction in speed or change in direction
- Sharp, rough, or adhesive surfaces, including surfaces made rough and/or made adhesive by airborne contaminants

Once particulate matter accumulation begins in a location, the initial accumulated material may accelerate the subsequent accumulation process.

2.2.1 Air Intake and Exhaust

Particulate matter accumulation can restrict air intake and exhaust ventilation openings. Restriction of these openings may increase pressure drop across ventilation openings and result in reduced airflow through the system and increased fan load.

2.2.2 Fans

Fans themselves are not particularly vulnerable to particulate matter. Fans installed directly on heat sinks may be affected by particulate matter accumulation on the heat sink, which can eventually, under rare circumstances, block fan rotation. However, particulate matter often affects fans indirectly. Restrictions of intake and outlet vents can alter a fan's pressure curve, resulting in greater fan loading. Changes in processor temperature as a result of blocked heat sinks can also trigger fan speed increases in systems equipped with fan speed controllers. These contamination issues may be misdiagnosed as fan problems.

2.2.3 Heat Sinks

One significant issue for air-cooled equipment is the effect of particulate matter on cooling efficiency and airflow through heat sinks. Microprocessor heat sinks often have dense stacks of thin metal fin plates. The narrow airflow channels in these heat sinks are especially vulnerable to blockage by airborne particulate matter. Particulate matter with significant fiber content is especially likely to accumulate on heat sinks. Fibers can become trapped against the leading edges of heat sinks, bridging the gaps between the fin plates. When additional fibers contact the initial fibers, they often become entwined. This process eventually results in a network of tangled fibers that acts as a trap for smaller particulates acting as an unintended filter. Particulate matter blockage can rapidly grow until airflow through the heat sink passages is essentially blocked, significantly degrading the cooling efficiency of the heat sink.

2.2.4 Magnetic Media and Optical Drive Mechanisms

Magnetic media drives are vulnerable to a number of contamination-related failure mechanisms. Particulate matter can accumulate in the grease used to lubricate the positioning and auto-loading mechanisms. This can cause abrasion or seizing of the moving parts. Some magnetic media can create its own contamination through oxide flake off. Particles can cause deformation of the media surface or interfere with head contact or spacing. In extreme cases, particulate matter may abrade read/write heads. Fixed-disk (hard) drives typically employ filters to avoid these vulnerabilities. Optical drives may experience similar abrasion or seizing of moving parts. In addition, particulate matter may interfere with the optical signal used to read and write data on the optical media.

2.2.5 Electrical Signals and Interconnects

Particulate matter with electrically conductive properties may provide unintended electrical paths within the IT and datacom equipment. In extreme cases, airborne particulate matter such as zinc whiskers or other conductive materials may form low-impedance short circuits within the IT and datacom equipment. Other effects may be less obvious, such as leakage paths provided by moisture-laden hygroscopic particulate accumulation. Of equal concern are electrically insulative particles, which can interfere with electrical connector contacts. Insulative particles may cause increased contact resistance or even open circuits. These effects may be intermittent in nature and can be very difficult to diagnose.

2.2.6 Corrosive Nature

Deliquescent relative humidity of a dust is the relative humidity of the air at which the dust absorbs enough moisture from the air to wet. If the relative humidity of the air is greater than the deliquescent relative humidity of the dust, equipment failure may occur because of the wetness of the dust from absorbed moisture. Hardware failures can occur in three ways:

- The wet ionic salts can have enough electrical conductivity to cause electrical failures through short circuits (Litvak et al. 2000).
- The wet ionic salts can provide the ionic medium through which metal ions can migrate to form metal dendrites that can cause electrical short circuits.
- Under rare circumstances, the wet ionic salts may corrode the hardware to create electrical opens.

While particle accumulation may occur on a time scale of years, change in electrical conductivity of the particles due to spikes in relative humidity can happen abruptly and have the potential to cause equipment failures.

2.2.7 Examples of Particulate Contamination

Figures 2.1 through 2.3 illustrate examples of particulate accumulation. These examples are from accelerated testing under extreme conditions, but similar patterns have been observed in equipment returned from heavily contaminated datacom equipment centers.

Figure 2.4 shows sodium chloride (white) dust electrostatically attracted to the 220 V cables in an IT equipment rack. Salts have also been observed to electrostatically segregate to high-voltage copper traces on power supply PCBs. If the relative humidity of the data center air is greater than the deliquescent relative

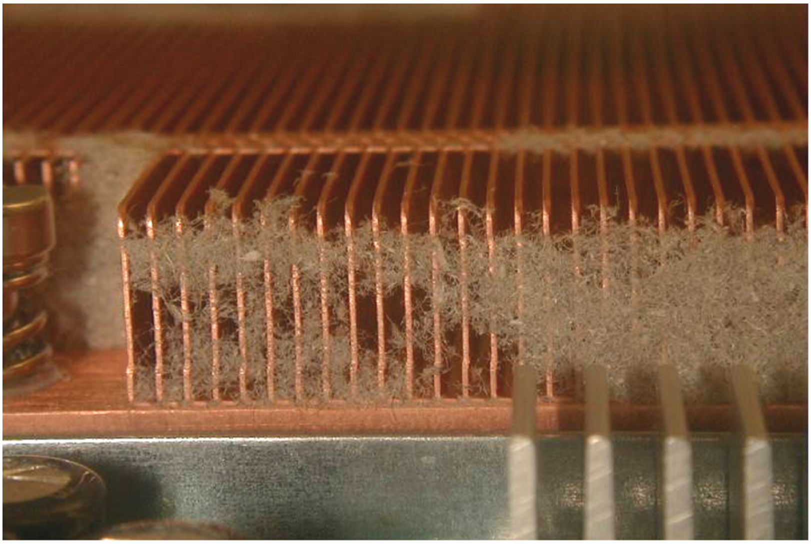


Figure 2.1 Particulate matter accumulation in a fine-pitch heat sink.

Figure 2.2 An example of unexpected dust accumulation around intakes. Particulate matter is shown in the small gap surrounding the connector sockets.

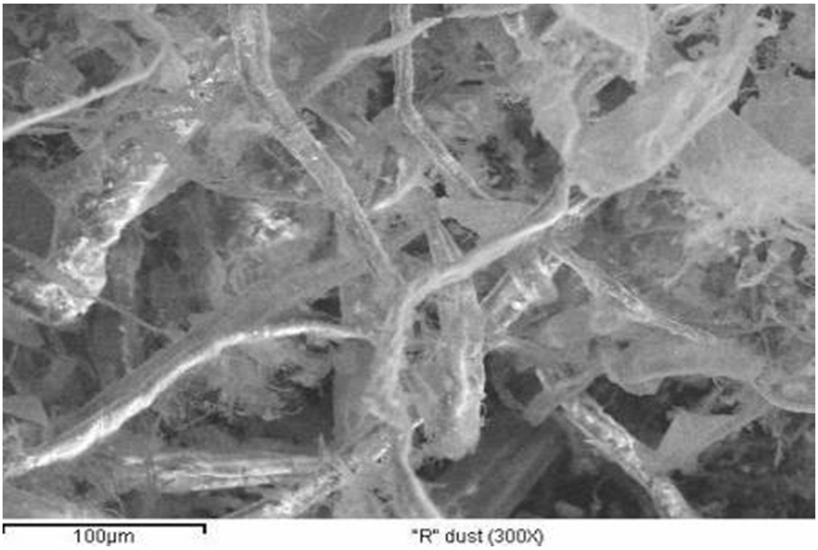


Figure 2.3 Scanning electron microscope (SEM) image of particulate matter accumulation from a heat sink. The intertwined fibers form a matrix that trap smaller particulates.

Figure 2.4 Sodium chloride dust on 220 Vac cables. The white deposits follow the high-electric-field pattern.

humidity of the dust on the PCBs, the hardware can fail due to one of the corrosion mechanisms listed in section 2.2.6.

Figure 2.5 shows an example of a zinc whisker. Zinc whiskers are known to cause electrical arcing across PCB features with high voltages across them. Cases of low-voltage circuits being damaged by zinc whiskers are hard to diagnose and therefore are not well documented in the published literature. Extensive field experience and laboratory experiments have led to the conclusion that the likelihood of zinc-whisker failures at voltages below 48 V is very low. The electric field in this low-voltage range is too weak to align the zinc whiskers to allow multiple whiskers to bridge the gap between the positive and negative features on electronic assemblies. Voltage below 48 V is also too low to cause arcing across the positive and negative features (White 2014).

2.3 GASEOUS CONTAMINATION

The effects of gaseous contamination, alone or in combination with particulate matter, may cause significant damage to datacom equipment.

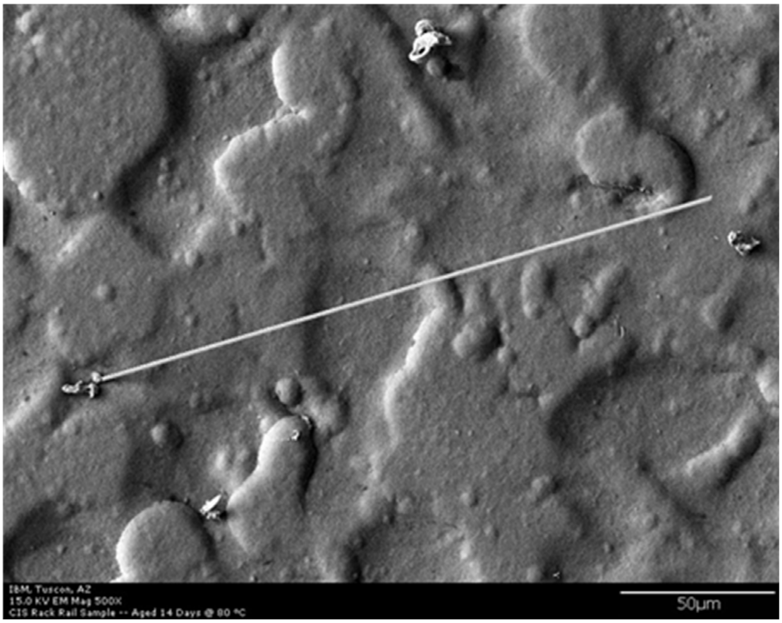


Figure 2.5 Zinc whiskers are small, electrically conductive filaments of zinc growing out of zinc electroplating. Zinc whiskers are sometimes found on the underside of zinc-electroplated floor panels. Zinc whiskers can typically be a micrometer in diameter and a millimeter long. These metallic filaments may become airborne if the surface with zinc whiskers is disturbed. Airborne introduction of zinc whiskers into IT and datacom equipment may result in arcing across features with high voltages across them.

The following information, initially published in *Design Considerations for Datacom Equipment Centers*, Second Edition (ASHRAE 2009b), provides typical characteristics of gases that result in corrosion of computer hardware.

Table 2.1 includes the most common and abundant corrosion-inducing gases that might be found in a datacom environment.

2.3.1 Corrosion Risks from Gaseous Contamination

Sulfur-bearing gases, such as sulfur dioxide (SO_2) and hydrogen sulfide (H_2S), are the most common gases corroding IT and datacom equipment (Rice et al. 1981).

The two common modes of hardware failures resulting from exposure to sulfur-bearing gaseous contamination are the creep corrosion of metallization on PCBs and

Table 2.1 Gases of Most Concern in the Datacom Equipment Center

Gases	Physical Characteristics	Corrosive Nature	Sources
Sulfur dioxide (SO_2)	Colorless gas, irritating pungent odor	Reacts with water to produce highly corrosive sulfuric acid	Product of combustion of fossil fuel and incineration of organic waste, also found in paper mills, tire factories, and oil refineries
Hydrogen sulfide (H_2S)	Colorless gas, odor of rotten eggs	Forms metallic sulfides	Intermediate in chemical synthesis
Chlorine (Cl)	Greenish-yellow gas, pungent, initiating, choking odor	Very reactive and produces corrosive metal salts, combines with all elements except carbon and noble gases	Widespread use in chemical synthesis, bleaching, oxidation
Hydrogen chloride (HCl)	Colorless, corrosive gas, pungent characteristic odor, fumes in air	Quickly soluble in water reacting to form hydrochloric acid, corrosion products are copper chloride and other metal salts	Chlorides and HCl are by-products of coal and incinerator combustion, widespread use in chemical synthesis, polymers, rubber, and pharmaceuticals
Nitrogen dioxide (NO_2)	Reddish brown gas, suffocating odor	Highly reactive, forms acid with water, corrodes electronic materials forming highly corrosive nitric acid	Used in chemical synthesis and explosives, product of combustion from energy production and automobiles
Ozone (O_3)	Characteristic pleasant odor in small concentrations	Most reactive form of oxygen, found in smog	Disinfectant for water and air, bleach for textiles, waxes, and oils
Ammonia (NH_3)	Colorless, corrosive alkaline gas, pungent odor	Readily dissolves in water and combines readily with acid gases, producing a corrosive salt	Refrigeration, fertilizers, synthetic fibers and plastics, widely used in chemical synthesis

Source: *Design Considerations for Datacom Equipment Centers*, Second Edition (ASHRAE 2009b).

the corrosion of miniature surface-mount technology (SMT) resistors that have silver metallization termination (Fu et al. 2012, Cole et al. 2010). An example of corrosion of copper on a PCB due to sulfur-bearing gases is shown in Figure 2.6. In this example, the copper sulfide corrosion product crept on the PCB and electrically short circuited some nearest neighbor features on the board. An example of SMT resistor corrosion as a result of sulfur-bearing gases emanating from volcanic activity is shown in Figure 2.7. The device in Figure 2.7 failed because sulfur-bearing gases corroded the silver metallization. The bottom half of the figure shows silver sulfide flowers extruding from under the dielectric insulation. The sulfur-bearing gases entered the component package and attacked the silver termination, forming silver sulfide (Ag_2S). Silver sulfide occupies a larger volume than the silver from which it originates. The mechanical pressure created by the Ag_2S formation inside the package damaged the mechanical integrity of the package, allowing the corrosive gases greater access to the silver termination, thus hastening the corrosion mechanism, leading to the ultimate failure of the device as an electrical open circuit. The frequency of occurrence of creep corrosion on PCBs rose dramatically with the adoption of the European Union Restriction of Hazardous Substance (RoHS) directive that took effect in July 2006 (RoHS 2003). The RoHS directive restricted the use of six hazardous materials in electronic hardware, of which lead metal was one. The

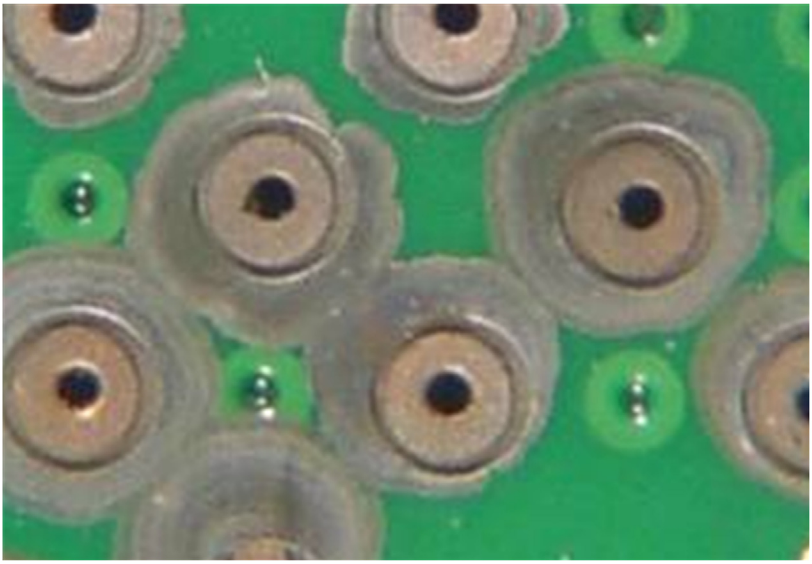


Figure 2.6 The optical micrograph shows copper sulfide corrosion product creeping on a PCB surface and electrically shorting nearest neighbor features.

higher melting range of lead-free solders compared to the lead-tin eutectic solder and the poor wettability of copper metallization by the lead-free solder led to changes in the PCB materials, finishes, and processes that made the RoHS-compliant PCBs more susceptible to creep corrosion. Other factors that contributed to the rise of copper creep corrosion occurrences are as follows:

- Increased airflow for thermal management
- Increased use of IT and datacom equipment in geographies with higher levels of sulfur-bearing gaseous pollution
- Continued reduction in spacing between conductors on PCBs

The increase in the occurrence of SMT resistor corrosion was not related to the adoption of the RoHS directive. Instead, it was due to the increased miniaturization of the resistors in combination with the increased use of IT and datacom equipment in geographies with higher levels of sulfur-bearing gaseous contamination.

Copper creep corrosion on PCBs and the corrosion of silver metallization in surface-mount resistors are the common modes of corrosion failures from which

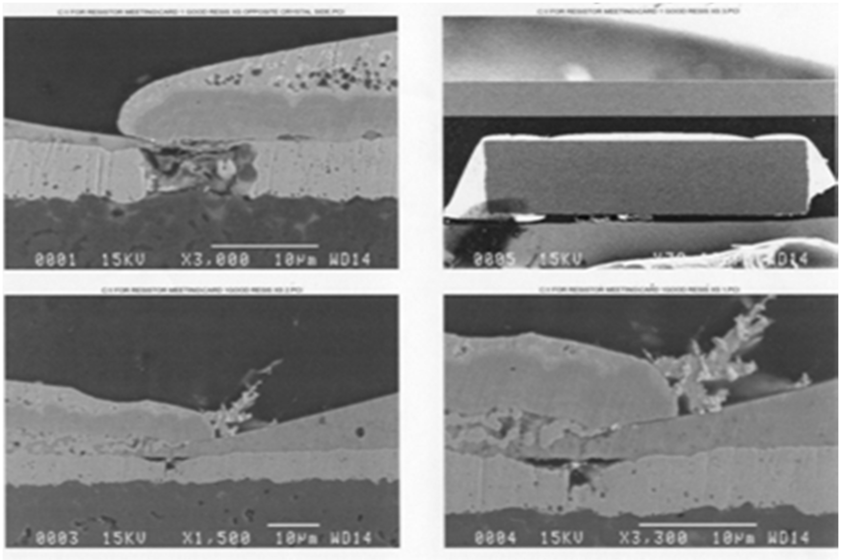


Figure 2.7 The top left and top right micrographs show the resistor cross section in low magnification. The bottom left and bottom right micrographs show silver sulfide flowers protruding out from under the dielectric insulation. The resistor terminal was electrically undermined by the formation of silver sulfide.

hardware is presently suffering. In the future, as the technology changes, the failure modes will change.

Solid particulate matter, especially fine dust, can play a synergistic role in aiding the corrosion of IT and datacom equipment. Particles can absorb moisture, especially when the room relative humidity is higher than the deliquescent relative humidity of the dust, which for fine particles typically found in urban, heavily polluted environments, is in the 50% to 65% range (Litvak et al. 2000). The fine dust chemical constituent of main concern is probably ammonium hydrogen sulfate because of its low deliquescent relative humidity of 40%. The high ionic content of the settled fine particles provides the electrolytic path for the metallic ions and corrosion products to creep on the PCB surfaces. Particles can also contribute to the degradation of hardware reliability two other ways: (1) particles on metal surfaces may increase the rate of metal corrosion by differential aeration-induced localized corrosion, and (2) by increasing the surface area for gas adsorption.

In summary, airborne particulate matter and gaseous contamination can affect IT and datacom equipment reliability in various ways. The degradation mechanism will vary depending on equipment location and the chemistry, quantity, and composition of the contaminants. Equipment reliability concerns arise from mechanical, chemical, or electrical degradation. Failures are often intermittent and difficult to diagnose. This is due, in part, to the interaction of multiple factors such as particulates, gases, and humidity that combine to trigger the failures.

To a certain extent, airborne contamination in datacom environments is inevitable. Nonetheless, every effort should be made to minimize airborne contamination. Contamination monitoring, prevention, and control are discussed in Chapters 4, 5, and 6, respectively.

3

Industry Specifications and Guidelines

This chapter summarizes typical cleanliness guidelines and limits intended for commercial and industrial environments to quantify tolerable exposure to particulate matter and gaseous contaminants. There are several published and accepted standards relevant to commercial and industrial environments that are extended to the datacom environment. Using multiple standards can make it difficult to establish a single set of contamination limits for the datacom industry, as contamination, concentration, composition, humidity, and thermal environment interactions vary within a facility. Also, one contaminant by itself may not be a significant problem, but when it is atomically combined with other environmental contaminants or with moisture, the combination may result in datacom equipment failures. Product design of datacom equipment is another related aspect since the materials, airflow paths, and types of cabinets (e.g., liquid-cooled or self-contained cabinets) can determine the susceptibility to particulate matter and gaseous contaminants.

3.1 PUBLISHED GUIDELINES AND LIMITS FOR PARTICULATE MATTER

3.1.1 GR-63-CORE/Network Equipment-Building Systems

As it applies to particulate contamination, *GR-63-CORE, Network Equipment-Building Systems (NEBS) Requirements: Physical Protection* (Issue 4, April 2012) defines the typical levels of particulate contamination expected in central offices and other environmentally controlled telecommunication equipment spaces located in densely populated urban environments (NEBS 2012). NEBS-63-CORE also defines the method for measuring particulate contamination levels and the hygroscopic dust test method to determine if the telecommunication equipment has been designed to withstand the expected level of airborne particulate contaminants. The NEBS requirements were created to ensure improved network robustness, simplified equipment installation, and to promote the economic planning, engineering, and operation of equipment spaces. The NEBS requirements for airborne contamination levels provide specific concentration limits for particles of various size ranges. These limits were incorporated into *Design Considerations for Datacom Equipment Centers*, Second Edition (ASHRAE 2009b). However, the NEBS limits do not indicate particle concentrations at which datacom equipment has been shown to fail. Rather, the requirements represent expected indoor concentrations when the datacom equipment center and equipment are located within densely populated urban environments that typically have high outdoor air pollution levels. The indoor concentrations were estimated using a material balance model, which assumed ventilation rates and filter efficiencies that may be common within telephone switching centers. Table 3.1 shows the average yearly expected indoor levels of particulate contaminants derived using predictive modeling and the 95th percentile values for these contaminants in the outdoor urban environment. That is, for 95% of the readings, the level of the particulate contaminant is lower than the listed value. The total suspended particulate (TSP) amount is the sum of suspended coarse particles (diameters >2.5 μm) and fine particles (diameters ≤2.5 μm). The predictive modeling is based on a building using a MERV 2 rated filter, continuously operating HVAC fans, and supply air consisting of 10% outdoor air and 90% recirculated air (NEBS 2012).

The total suspended particulate level is measured using a dichotomous sampler that separates particles into two size ranges: fine particles (diameters ≤2.5 μm) and coarse particles (diameters > 2.5 μm), using polytetrafluorethylene filters that are weighed before and after a certain known volume of air has passed through them from 1 to 7 days. The NEBS document GR-63-CORE does not deal with the chemistry of the particulate contamination besides stating the concentrations of the water-soluble salts, sulfates, and nitrites typically found in the fine-particles portion of the suspended particles in datacom equipment centers located within densely populated urban environments that typically have high outdoor air pollution levels.

Table 3.1 NEBS Indoor Particulate Contaminant Levels

Contaminants	Concentration
Airborne total suspended particulates (TSPs)	20 $\mu g/m^3$
Coarse particles	< 10 $\mu g/m^3$
Fine particles	15 $\mu g/m^3$
Water-soluble salts	10 $\mu g/m^3$
Sulfate	10 $\mu g/m^3$
Nitrites	3 $\mu g/m^3$

Source: *GR-63-CORE* (NEBS 2012).

The NEBS document GR-63-CORE provides a test method to determine whether the telecommunication equipment can withstand the hygroscopic dust levels found in typical telecommunication equipment centers. Details of the test method are provided in GR-1274-CORE (NEBS 2012).

3.1.2 IEC Standard 60721-3-3

International Electro-Technical Commission's (IEC) IEC Standard 60721-3-3, *Classification of Groups of Environmental Parameters and Their Severities—Stationary Use at Weather-Protected Locations* standard consists of multiple sections that define typical environments that equipment may be exposed to (IEC 2002). The standard also classifies groups of environmental parameters and the severities to which products are subjected when mounted for stationary use (permanently or temporarily) at weather-protected locations under specific use conditions, including periods of erection work, down time, maintenance, and repair. The standard is based on information acquired from actual field measurements worldwide. Section 3.3 of IEC Standard 60721-3-3 covers the likely range of contaminants and other environmental parameters in a number of typical weather-protected environments ranging from controlled datacom equipment center environments to crude structures with little more than a roof. Environmental conditions directly related to explosion hazards, fire extinguishing, and ionizing radiation are excluded. Only those environmental conditions listed in Table 3.2 are considered. No special explanations of the effects on the products for these conditions are discussed in the standard (IEC 2002).

The standard defines the usage environment by breaking it down into environmental parameters. Table 3.2 shows a list of the specific parameters covered in the standard.

The list in Table 3.2 is very comprehensive. Each of these conditions has a range of severities with corresponding measurable levels. IEC Standard 60721-3-3 (IEC 2002) contains a set of tables specifying the severity levels typically associated with various real-world situations. The severities specified are those that will have a low probability of being exceeded.

Specifying a set of environmental class conditions brings about levels for each of the classes in Table 3.2. This includes specifying not only contaminants but also ambient environmental specifications.

The process used by manufacturers to specify a complete environment is fairly straightforward:

1. Determine the type of environment in which the product will operate, following the suggestions in IEC Standard 60721-3-3 (IEC 2002).
2. Find the corresponding set of environmental conditions.
3. Make exceptions as needed to suit the product requirements.

Table 3.2 Environmental Parameters of IEC Standard 60721-3-3

Code	Parameter	Covers
K	Climatic conditions	Temperature, humidity, temperature change rate, air pressure, solar radiation, heat radiation, air movement, condensation, wind-driven precipitation, water from sources other than rain, and formation of ice
Z	Special climatic conditions	Modifies climatic conditions of a particular class combination
B	Biologically active conditions	Flora (e.g., mold and fungus) Fauna (e.g., rodents and termites)
C	Chemically active conditions	Sea salts and pollutants (sulfur dioxide, hydrogen sulfide, chlorine, hydrogen chloride, hydrogen fluoride, ammonia, ozone, and nitrogen oxides)
S	Mechanically active conditions	Sand and dust
M	Mechanical conditions	Stationary vibration and nonstationary vibration

Source: IEC Standard 60721-3-3 (IEC 2002).

3.1.3 ISO Standard 14644-1 Cleanrooms and Associated Controlled Environments—Part 1: Classification of Air Cleanliness

ISO Standard 14644-1 (ISO 1999) has become the dominant, worldwide standard for classifying the cleanliness of air. This standard uses the airborne particle limits to classify cleanrooms and associated controlled environments, such as datacom equipment centers, exclusively in terms of concentration of airborne particles. Examples of controlled environments include not only cleanrooms but also datacom equipment centers, telecom/datacom closets and telecom/datacom switching centers. Table 3.3 provides maximum concentration levels for each ISO class. For a given particulate size, each successively higher classification allows approximately ten times as many particles as the previous class. The ISO classes are based on the following formula:

$$C_n = 10^N (0.1/D)^{1.08} \tag{1}$$

where

C_n = maximum permitted number of particles per m^3 equal to or greater than the specified particle size, rounded to a whole number

N = ISO class number

D = particle size, μm

Table 3.3 ISO Standard 14644-1: Selected Airborne Particulate Cleanliness Classes for Cleanrooms and Clear Areas

ISO Class	Maximum Number of Particles in Air (Particles in Each Cubic Metre Equal to or Greater than the Specified Size)					
	Particle Size					
	> 0.1 µm	> 0.2 µm	> 0.3 µm	> 0.5 µm	> 1 µm	> 5 µm
Class 1	10	2				
Class 2	100	24	10	4		
Class 3	1000	237	102	35	8	
Class 4	10,000	2370	1020	352	83	
Class 5	100,000	23,700	10,200	3520	832	29
Class 6	1,000,000	237,000	102,000	35,200	8320	293
Class 7				352,000	83,200	2930
Class 8				3,520,000	832,000	29,300
Class 9					8,320,000	293,000

Note: Uncertainties related to the measurement process require that data with no more than three significant figures be used in determining the classification level.
Source: ISO Standard 14644-1 (ISO 1999).

Datacom equipment centers must be kept clean to meet the cleanliness requirements of ISO Class 8 (Ortiz 2006). Class 8 allows 3,520,000 million particles 0.5 µm or larger per cubic metre. Class limits must be met with the strictness of the 95% upper confidence limit. Chapter 4 of this book discusses particulate contamination monitoring and analysis.

3.1.4 ANSI/ISA Standard 71.04-2013

ANSI/ISA Standard 71.04-1985 has been one of the most widely used standards for the protection of electronic hardware in industrial process measurement and control systems (ISA 1985). The standard was updated in 2013 to include the protection of the RoHS-compliant electronic equipment. The standard was expanded to include computers in mission-critical data centers, as will be explained in Section 4.3 on gaseous contamination. The airborne particulate portion of the standard was also modified. It includes the following statement: "Dust that may be benign when dry can become corrosive in environments with relative humidity levels above the deliquescent relative humidity of the dust. Annex A describes a technique that can be used to measure the deliquescent relative humidity of dust" (ISA 2013).

In the ISA-71.04-2013 standard, the solid airborne contaminants are classified in terms of size and concentration, irrespective of the chemical or physical nature of the particles, as shown in Table 3.4 (ISA 2013). There is no explanation of the severity level class in terms of its effect on hardware reliability.

3.2 PUBLISHED GUIDELINES AND LIMITS FOR GASEOUS CONTAMINATION

Established gaseous composition environmental limits, listed in Table 3.5, from standards such as IEC Standard 60721-3-3 (IEC 2002) and GR-63-CORE (NEBS 2012) were developed for telephone switching centers and the equipment producer's own internal standards. The standard that most applies to gaseous contamination in datacom environments is the International Society of Automation's ANSI/ISA Standard 71.04-1985, *Environmental Conditions for Process Measurements and Control Systems: Airborne Contaminants* (ISA 1985). The 1985 version of the ISA standard establishes environmental corrosion levels by measuring the rate of corrosion product buildup on copper in terms of ångströms per month and classifies the contaminant severity levels into one of four classes: G1, G2, G3, or GX, as defined in Table 3.6. Severity level G1 is the only level acceptable for mission-critical data centers where corrosion should not be a factor determining equipment reliability. In other words, in mission-critical data centers, hardware should not fail because of corrosion.

The ISA-71.04-1985 standard was modified in 2013 to accommodate the significant increase in early life corrosion-related failures that resulted from two major factors: one was the move away from lead-tin solder to lead-free solder to comply with the European Union Restriction of Hazardous Substances (RoHS) directive (RoHS 2003), the other factor was the dramatic growth of the computer markets in Asian countries with environments high in sulfur-bearing gases emanating from coal-fired power plants. The high corrosion-related failure rates prompted ISA to undertake a revision to ANSI/ISA Standard 71.04-1985 (ISA 1985) to include silver corrosion rates along with copper as a measure of the severity level of the air in a data center (ISA 2013).

Table 3.4 ANSI/ISA Standard 71.04-2013 Classification of Airborne Particles

		Severity Level, $\mu g/m^3$			
Particle size	**Class**	**1**	**2**	**3**	**4**
>1 mm	SA	<1000	<5000	<10000	µ 10000
0.1 to 1 mm	SB	<500	<3000	<5000	µ 5000
1 to 100 µm	SC	<70	<200	<350	µ 350
<1 µm	SD	<70	<200	<350	µ 350

Source: ANSI/ISA Standard 71.04-2013 (ISA 2013).

According to the revised ASNI/ISA Standard 71.04 standard, the copper and silver corrosion rates must be less than 300 and 200 Å/month, respectively, for the air in a mission-critical data center to be considered acceptable. The data center survey conducted to arrive at these acceptable corrosion rates is described in Chapter 4.

Table 3.5 Published Gaseous Contaminants for IT Equipment

Gas	IEC Standard 60721-3-3 (IEC 2002)	GR-63-CORE (Telcordia 2006)	ISA Standard 71.04-1985 (ISA 1985)	One Manufacturer's Internal Standard
Hydrogen sulfide (H_2S)	10 µg/m^3	55 µg/m^3	4 µg/m^3	3.2 µg/m^3
Sulfur dioxide (SO_2)	100 µg/m^3	131 µg/m^3	26 µg/m^3	100 µg/m^3
Hydrogen chloride (HCl)	100 µg/m^3	7 µg/m^3	—	1.5 µg/m^3
Chlorine (Cl_2)	100 µg/m^3	14 µg/m^3	3 µg/m^3	—
Nitrogen oxides (NO_X)	—	700 ppb	50 ppb	140 µg/m^3
Ozone (O_3)	10 µg/m^3	245 µg/m^3	4 µg/m^3	98 µg/m^3
Ammonia (NH_3)	300 µg/m^3	348 µg/m^3	348 µg/m^3	115 µg/m^3
Volatile organics (C_XH_X)	—	5000 µg/m^3	—	—

* Total HCl and Cl_2.

Table 3.6 ISA Standard 71.04-1985 Corrosion Class Levels

ISA Class	Level	Description
G1	Mild	Corrosion is not a factor in determining equipment reliability
G2	Moderate	Corrosion is measurable and may be an issue in five years
G3	Harsh	It is probable that corrosion will occur within five years
GX	Severe	Only specifically designed and packaged equipment will survive

Source: ANSI/ISA Standard 71.04-1985 (ISA 1985).

The gaseous contamination limits in Table 3.5 serve as a guide for specifying telecommunications equipment center environmental cleanliness, but they are not useful for surveying the corrosivity of data center air or predicting the failure rates of hardware in the telecom environment for two reasons. First, gaseous composition determination is not an easy task. Second, there is no known, reliable mathematical relation that can be used to predict the rate of corrosion from the concentration of gaseous contaminants. The lack of a relationship between copper and silver corrosion rates and gaseous composition arises from the synergistic effects between gases. For example, it has been demonstrated that hydrogen sulfide (H_2S) and sulfur dioxide (SO_2) alone are not very corrosive to copper or silver, but the combination of these gases with other gases such as nitrogen dioxide (NO_2) and/or ozone (O_3) are much more corrosive to these metals (Volpe 1989). Neither sulfur dioxide (SO_2) nor nitrous oxide (NO_2) alone is corrosive to copper, but together they attack copper at a very rapid rate (Johansson 1985).

3.3 APPLICATION OF INDUSTRY SPECIFICATIONS AND GUIDELINES

The published industry specifications and guidelines described in this chapter were considered in establishing the acceptable limits of particulate and gaseous contamination in data centers, as described in Chapter 4 and in the 2011 ASHRAE white paper titled, "Gaseous and Particulate Contamination Guidelines for Data Centers" (ASHRAE 2011a).

Chapter 5 suggests ways to limit the concentrations of particulate and gaseous contaminations to within acceptable limits through prevention and some control practices. Chapter 6 covers the particulate and gaseous contamination control through more active means. Chapter 7 describes the contamination prevention and control in data centers that resort to air-side economizers to conserve energy.

4

Contamination Monitoring and Analysis

The objective of datacom equipment center contamination analysis is to determine the presence and the sources of contamination and the degree to which the contaminants will degrade the reliability and life expectancy of the IT and datacom equipment.

A datacom equipment center contamination analysis should begin with a visual survey of the datacom equipment center to help plan a course of action. The main elements of a site's visual inspection and general audit are as follows:

- environmental history of the data center
- ventilation system and layout of the data center
- choice of sampling locations

The environmental history of a datacom equipment center includes the history of the datacom equipment and infrastructure hardware failures, temperature and humidity records, and complaints about odors. A list of construction and maintenance projects that may have exposed equipment to contamination must be compiled. Special attention must be paid to the history of the heating, ventilation, and air-conditioning (HVAC) equipment maintenance and the filter replacement. Drywall construction or other changes to the walls and airflow containment structures must be noted. There have been known cases of drywall emitting sulfur-bearing gases (Schmit 2009).

The IT and datacom equipment failure reports for trends or clues about environmental causes must be examined. Often, the failure root cause analysis of field-returned hardware may identify a chemical species, gas, or settled dust that may have interacted with and caused the hardware to fail. The datacom equipment center visual survey may help identify the potential sources of the gaseous and/or particulate contamination.

The ventilation system and layout of the datacom equipment center should be mapped to document the airflow pattern. The locations of computer hardware, tape drives, disk drives, printers, administrative areas, air diffusers, modular air-conditioning units (MACUs), and HVAC units should be included on the layout drawing. There are several notable areas to examine specific to the HVAC system:

- The air distribution system of the building should be mapped including the level of air filtration, the areas with shared air return, the volume of outdoor air used, and the locations of the outdoor-air intakes. Air distribution ducts, subfloors and plenums should be examined for cleanliness.
- Air filters should be inspected to verify that they are the correct type and that they are being well maintained and regularly serviced. Inspection can include direct visual observation of dust loading and measuring the pressure drop across the filters.
- Air humidifiers can release salts into the environment. The water used for humidification may be high in salts. The evaporating airborne water droplets can leave behind tiny particles of salt that can be blown into the data center environment. These salts can cause serious corrosion and ion migration threats and can electrically short circuit and/or corrode printed circuit boards (PCBs). The incoming water quality and condition of water filtration and humidification equipment should be inspected for abnormal operation or contamination. The equipment service records should be checked. The ductwork near the humidifiers should be checked for signs of mineral accumulation, which may indicate poor quality water being used for humidification.

Once the history and the layout of the datacom equipment center have been obtained, documented, and analyzed, it is necessary to choose the locations where contamination monitors should be placed and the dust collected.

Air-monitoring devices for particulate and gaseous contamination should be placed primarily in front of the datacom equipment racks where the air enters the racks. Additionally, air-monitoring devices may be placed at the following locations:

- Immediately downstream of filters, MACUs, HVACs units, and humidifiers
- At the entry doors to the data center
- In the spaces between the administrative areas and datacom equipment
- In areas around the datacom equipment
- In areas around the printers

Dust samples should be collected from the following:

- air filters
- internal surfaces of the IT and datacom equipment
- internal surfaces of humidifiers and HVAC equipment

- under raised-access floor surfaces and the floor support grids and stanchions
- internal surfaces of ductwork near the datacom equipment

The equipment and procedures for monitoring and analyzing particulate and gaseous contamination are addressed in this chapter.

4.1 PARTICULATE MATTER ANALYSIS

4.1.1 Airborne Dust

There are two major methods for evaluating airborne particulate contamination: gravimetric method and airborne particle counters.

The gravimetric method was commonly used in the earlier days of particulate matter analysis. In this method, preweighed test filters are used to capture particles from a given volume of air using a vacuum pump and the weight gain is used to calculate the total suspended particulate content per unit volume of air. A variation on the method has multiple filters in series, with each downstream filter capturing a smaller size range of particles than the preceding one. Particle size distribution can thus be determined. The particle debris on a single filter or multiple ones in series can be later examined in a laboratory to determine the number, the size, and the chemistry of the particles. Microscopic examination of the particles collected on a filter paper is still the best way to learn the specific chemical nature of the particles, which may help determine the corrosivity and the source of the particles. The gravimetric method is fairly inexpensive and can be deployed as a long-term monitoring method, but it does not offer real-time particle contamination information. Another shortcoming is that it can analyze only a small fraction of the air in the data center. The method reveals longer-term history, not the real-time and current particle events.

Airborne particle counters (APC) were developed in the mid-1950s to monitor instantaneous particle concentration levels and provide quick response when contamination levels exceed acceptable limits. Instead of waiting days for the laboratory to return the gravimetric method results to the field, airborne particle counters almost instantaneously provide particle concentration values. Airborne particle counters count the number of particles in the air per unit volume on a real-time basis. Some can also determine the particle size distribution by counting particles in various size ranges, also called bins. An airborne particle counter is a relatively simple device in principle. A pump brings air into a fixed volume at a constant rate for a certain period of time. A laser beam illuminates the particles. Light is scattered or absorbed by the particles. A photodetector responds to the flash of scattered light producing an electric signal or pulse. The magnitude of the pulse is proportional to the intensity of the scattered light, which in turn is roughly proportional to the size of the particle scattering the light. For each particle that passes through the counter chamber, an electric pulse is thus produced with its magnitude roughly proportional to the size of the particle. The electric pulses from the photodetector are sent to a pulse height analyzer that examines the magnitude of the pulse and places it into an appropriate size channel, called a bin. Each bin corresponds to a pulse height range, and in turn, to a particle size range. As the counting continues, the numbers in the bins increase, giving a particle size distribution of the particulate contamination that flowed through the counter.

Particle counter pumps operate at a constant speed. The speed varies by manufacturer and model but is generally 0.1 to 1 cfm (0.00283 to 0.0283 m^3/min). Particle counters are able to differentiate particle size via their channels. Each channel can analyze a specific size range of particles such as 0.1 to 0.2, 0.2 to 0.3, 0.3 to 0.5, 0.5 to 1.0, 1 to 5 and >5 μm. Counter models can have one to six channels or more. Some APCs can give data for each channel in real time so that all particle sizes can be monitored in real time. Other APCs give only an average of all particle sizes (Akey 2005).

One of the limitations of airborne particle counters (APCs) is that the amount of light a particle scatters into the photodetector depends on the shape of the particle and its reflectivity. Shiny particles reflect more light and will appear larger than their actual size. Particles with dull surfaces, such as carbon particles, will reflect less light and will appear smaller than their actual sizes.

Another shortcoming of airborne particle counters is that they can analyze only a small fraction of the air in the data center. For example, in a 1000 m^2 (10,761 ft^2) datacom equipment center with 3 m (9.8 ft) high ceiling, a 0.028 m^3/min (1.0 cfm) airborne particle counter will analyze only 0.0283/3000 = 1/106007 (or 0.0009%) of the air in the room in one minute. A number of airborne particle concentration readings have to be taken spatially spread out across the whole room to statistically represent the entire volume of air in the room. ISO Standard 14644-1 standard recommends sampling several different locations in the room (ISO 1999). It suggests that the number of samplings be equal to the square root of the room area in square metres. For example, if the room area is 1000 m^2 (10,761 ft^2), the number of samplings are suggested to be $\sqrt{1000} \approx 32$ to get a statistically valid representation of the particulate contamination in the datacom equipment center.

There are three main types of particle counters: handheld, portable, and remote (Akey 2005). Handheld devices are small, handy devices that are convenient for taking quick measurements at various locations in the datacom equipment center. While they do not have the functionality of a larger portable model, many handhelds can collect data similar to that of the portable units. Handheld devices generally take readings at several-second intervals. They typically have air-sampling pumps designed for intermittent use, but are not suitable for long-term deployment.

Portable devices are bigger devices that can be powered by a wall outlet or a rechargeable battery. They are useful for long-term monitoring. Data can be collected and stored in the counter for analysis at a later date.

Remote airborne particle counters allow for multipoint monitoring, with the collected data reported back to one central location. This is generally required for cleanroom facilities that need constant monitoring on a real-time basis. Particle sensors are placed around the room and data is transmitted and collected centrally.

Particle count monitoring in a datacom equipment center is generally not needed on a daily basis. Monitoring is required when there is a notable problem that could have been caused by contaminants. While a handheld device can be helpful for periodic site checkups, a portable device will work best for longer-term troubleshooting. If possible, choose a counter that can track several particle sizes so the data will include the count for each size range instead of just one total average value.

Measurements should be taken over one to two weeks at a time. If possible, measurements should be taken throughout the year, because weather and seasons can affect the concentration and size distribution of particles in a datacom equipment center.

Take as many readings as possible throughout the data center. The following areas are recommended to characterize a data center (Krzyzanowski and Reagor 1991):

- Doorways
- Human activity/high-traffic areas
- Under diffusers
- Inlet and outlet of AHU
- Outdoors at the makeup air entry

The outdoor particulate count is important for normalizing data taken at different times of day or during different seasons. The outdoor air may affect the indoor air quality. If there is a noticeable spike in indoor air particles, comparing the indoor data with outdoor data can help determine the source of the particles. If the outdoor particle count increased in unison with the indoor particle count, it is likely that the indoor particles were the result of outdoor air entering the datacom equipment center. If the outdoor source stayed the same while the indoor count increased, it is most likely that the problem was not caused by outdoor conditions (Krzyzanowski and Reagor 1991).

4.1.2 Settled Particulate Matter

Generally, a contamination event such as from construction activity in the datacom equipment center has already occurred before the analysis team arrives on the scene. By the time the analysis team arrives, the particulate contamination has settled on the datacom equipment and on the room infrastructures. There are also cases where there is no single major contaminating event, but where dust has collected over a period of time and has come to the attention of the datacom equipment center administrator, who has become concerned with the level of visible dust deposited on the equipment. The analysis team is assigned the responsibility of determining the source of the contamination, and equally importantly, its effect on the IT and datacom equipment's reliability. Sometimes, a contaminating event such as a fire may have occurred, and the smoke emanating from the fire may have contaminated some of the neighboring equipment. The challenge then is to determine the level of contamination on the various pieces of equipment and to decide which ones may need to be cleaned.

As described in Chapter 2, particulate matter related failures can be due to mechanical, chemical, or electrical effects. Here, we discuss the chemical effect related to the ionic content of the settled dust. It is the ionic content of the dust that makes it corrosive to metals. One method of determining the ionic content of settled dust and mapping it across the data center is as follows: start with a small, clean bottle with a clean sponge swab on a stick attached to the bottle cap. Fill the bottle with 10 mL distilled or deionized water with known electrical conductivity. The conductivity of water should be less than 1 μS/cm. Place a stencil, made of thin stainless steel foil with a 1 cm^2 square opening, in intimate contact with the surface where contamination measurement is desired. Other appropriate stencil opening sizes may also be used. Swab the surface exposed through the stencil with the sponge multiple times. After each swab, return the sponge to the bottle to transfer the contamination to the water in the bottle. Ensure that all the contamination has been transferred to the water in the bottle and return the sponge swab to the bottle. Measure the electrical conductivity of the water in the bottle. Knowing the electrical conductivity of the water before and after the swabbing operation, the ionic content of the 1 cm^2 surface can be obtained in terms of micrograms per square centimetre ($\mu g/cm^2$) NaCl equivalent. Contamination levels greater than 10 $\mu g/cm^2$ NaCl equivalent are considered corrosive to electronic hardware (Singh 2013).

It must also be noted that the dust must get wet to be corrosive. Therefore, the deliquescent relative humidity of the dust, which is the minimum relative humidity of the air in which the dust gets wet, must also be determined to know the corrosivity of the dust.

By mapping the contamination levels of dust in terms of $\mu g/cm^2$ NaCl equivalent, the source, the location, and the intensity of the dust-creating event can be gaged in terms of the contamination levels of the affected IT equipment. The IT equipment that needs cleaning can thus be identified.

4.1.3 Corrosivity of Particulate Matter

Dust is ubiquitous. Fortunately, not all dust is corrosive. Most dust is benign, rarely does particulate matter cause IT and datacom equipment to corrode and fail. Discussed here, in detail, is a method for determining the corrosive nature (chemical effect) of particulate matter.

Some fraction of settled dust on electronic hardware, such as PCBs, may consist of ionic salts which, under high humidity conditions, can absorb enough moisture to get wet and become electrically conductive, causing the hardware to fail by shorting neighboring features on the PCB (Weschler 1991, Likvak et al. 2000). Often, this failure is temporary. The hardware may recover to normal operation when the humidity level drops low enough to dry the particulate matter and make it electrically nonconductive.

The relative humidity above which the particulate matter absorbs enough moisture to get wet, and therefore become electrically conductive, is termed the deliquescent relative humidity (or critical relative humidity) of the dust. As an example, sodium chloride, also known as common salt, has a deliquescent relative humidity of about 75% at room temperature. Below this relative humidity, common salt is dry and electrically nonconductive, above this relative humidity, it is wet and electrically conductive. The electrical conductivity of wet particulate matter containing ionic species arises from the mobility of the anions and cations in the aqueous medium.

Deliquescent relative humidity is a convenient measure of the relative humidity above which the particulate matter will be corrosive. It can be determined by measuring and plotting the electrical conductivity of the particulate matter as a function of relative humidity. A detailed description of the procedure is as follows:

- The measurement test vehicle is a silver-plated interdigitated comb pattern on a PCB, as shown in Figure 4.1. The interdigitated combs are spaced 0.5 mm apart. For there to be electrical conduction across this 0.5 mm gap, a conductive media must bridge the gap. Wires are soldered to the two interdigitated comb patterns using rosin mildly activated flux. The test PCB is cleaned using isopropyl alcohol.

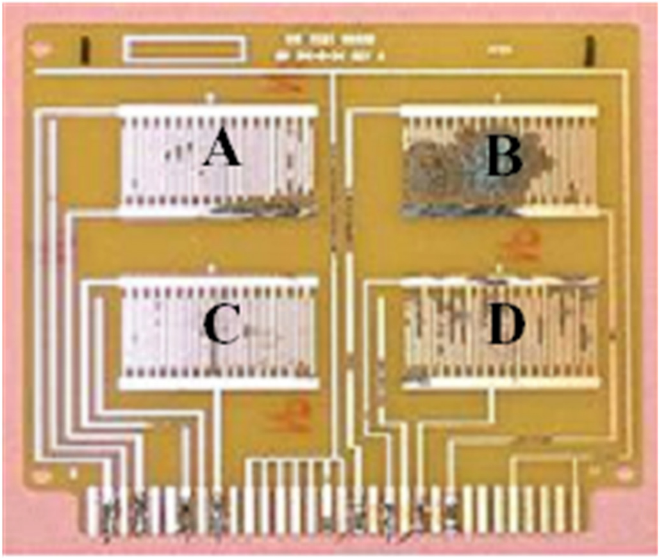


Figure 4.1 Interdigitated PCB (IPC-B24 test board) after a deliquescent relative humidity test.

- The interdigitated comb area of the PCB is covered with the particulate matter under test. There should be enough particulate matter for it to physically bridge the gap between the two combs.
- The test PCB is inserted in to a chamber at a low percentage relative humidity (typically 35%) and room temperature and allowed to equilibrate overnight.
- 10 V is applied across the comb patterns and leakage electric current is plotted versus time. The leakage current through dry dust will be in the picoAmpere range. The leakage current in wet dust will be in the microAmpere range.
- Relative humidity is elevated every 8 to 24 hours in approximately 10% steps.
- The leakage current at each relative humidity is noted and plotted versus relative humidity. The relative humidity at which the leakage current rises sharply is the deliquescent relative humidity of the dust under test.

Figure 4.2 shows a plot of leakage current obtained sequentially under different relative humidity values for a settled dust specimen collected from a datacom equipment in the field. The relative humidity was raised in steps from 35% to 83%, each step lasting for a day. Notice that the leakage current through the dust rose sharply at about 70% relative humidity and then dropped when the humidity was raised to 83%. This behavior of the leakage current rising sharply at a certain relative humidity and then dropping when the humidity is raised needs further study. The drop in

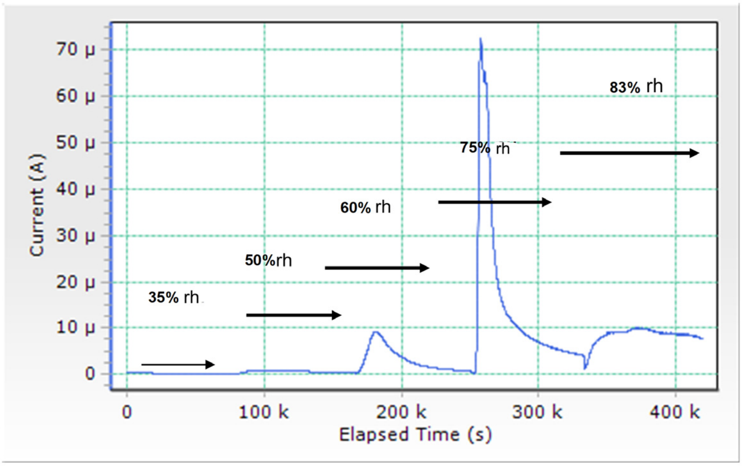


Figure 4.2 Leakage current, across 0.5 mm gap between interdigitated comb patterns, as a function of time with relative humidity increased in steps, each step lasting 24 hours. Note the abscissa is in terms of thousands of seconds.

the leakage current at high humidity may be due to the depletion of the mobile ions between the interdigitated combs.

The data of Figure 4.2 are replotted in Figure 4.3 as leakage current versus humidity. The plot shows a deliquescent relative humidity of about 60%. If a datacom equipment center is contaminated with this particulate matter, the reliability of the datacom equipment will not be degraded by the particulate matter if the relative humidity in the datacom center is kept below 60%.

A study at AT&T Bell Laboratories (Comizzoli et al. 1993) showed that, for various locations worldwide, leakage current due to the dust settled on electronic hardware increased exponentially with relative humidity. The study led to the conclusion that maintaining the relative humidity below about 60% in a datacom equipment center will keep the leakage current through settled dust in the acceptable sub-microampere range. However, there have been occurrences of dust with much lower deliquescent relative humidity contaminating the IT and datacom equipment and causing equipment failures. The source of these salts with low deliquescent relative humidity have often been the waters feeding the humidifiers. One such problematic salt is magnesium chloride. It is recommended that reverse-osmosis-cleaned water be used for humidification to eliminate these hardware failures.

4.1.4 Particulate Matter Chemical Analysis

Dust specimens collected from a datacom equipment center can give important clues about their origins and their potential threat to IT and datacom equipment's

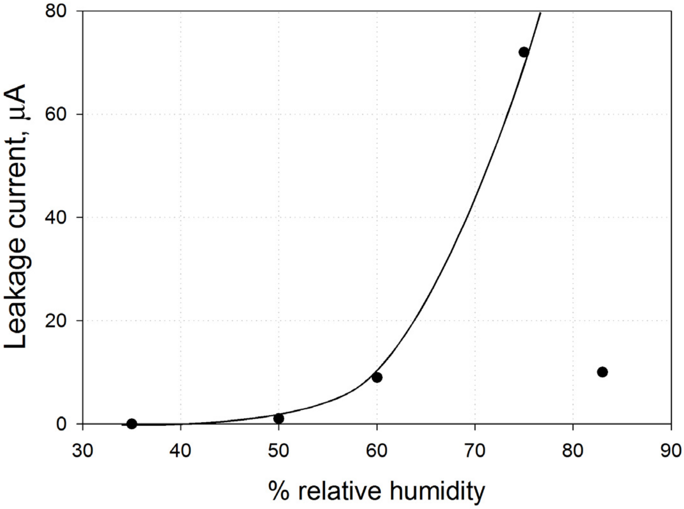


Figure 4.3 Leakage current, across 0.5 mm gap between interdigitated comb patterns, as a function of relative humidity.

reliability. Samples can be characterized for relevant characteristics that might cause mechanical, chemical, or electrical issues in the installed equipment.

Identification of the chemistry of dust specimens serves two useful purposes. By examining the chemistry of the dust, one can identify its ionic characteristics and, as a result, its tendency to cause electrical shorts on PCBs. Dust chemical analysis also helps identify the origin of the dust.

Often, the quantity of dust that can be collected for analysis is not enough to coat the interdigitated comb patterns to determine its deliquescent relative humidity. Chemical analysis is then the main means, though not a satisfactory one, of identifying the corrosive nature of the dust.

Chemical analysis of settled dust is accomplished by collecting the dust on an electrically conductive sticky tape stud that is later examined in a laboratory using a scanning electron microscope (SEM). The electrically conductive sticky tape eliminates the need to carbon coat the dust particles that, being generally nonconductive when dry, would otherwise electrically charge when exposed to the SEM electron beam. The energy dispersive x-ray (EDX) spectrum of the dust, which is displayed as counts versus the energy of the x-rays, identifies the elements in the dust and provides a rough indication of their concentration. From the elements in the dust and their approximate concentration, an assessment can be made of the chemistry of the dust. For example, if the elements in the dust are mostly magnesium and chlorine, it can be concluded that the dust is most probably magnesium chloride ($MgCl_2$). Given that $MgCl_2$ adsorbs moisture from the air at relative humidity as low as 35%, $MgCl_2$ will get wet and become electrically conductive in a typical datacom equipment center environment with relative humidity in the 45% to 55% range. The electrically conductive bridge formed by wet dust between features on a PCB may cause the datacom equipment to fail.

Chemical analysis of settled dust also helps to identify the source of the dust. For example, dust could originate from the concrete pavement outside the building and be carried into the datacom equipment center by personnel traffic, from human activity in or near the datacom equipment center, from soil near the air-intake duct, or from water used to humidify the data center air. The EDX elemental spectrum of the dust can be compared to the elemental spectrum from the various suspected sources to identify the source of the settled dust.

4.2 GASEOUS CONTAMINATION ANALYSIS

Sulfur-bearing gases, such as sulfur dioxide (SO_2) and hydrogen sulfide (H_2S), are the most common gases causing corrosion of electronic equipment (Rice 1981). An example of corrosion due to gaseous contamination on a circuit board compliant with the Restriction of Hazardous Substances Directive (RoHS) (RoHS 2003) is shown in Figure 2.6.

Gaseous contamination limits have been published in ANSI/ISA Standard 71.04-2013 standard (ISA 2013). These limits serve as guides for specifying data center air cleanliness, but they are not useful for surveying the corrosivity of air or predicting the failure rates of IT and datacom equipment for several reasons. First, gaseous composition determination is not a trivial task. Second, it is generally not a straightforward exercise to predict the rate of corrosion or the impact on hardware reliability from gaseous composition. An added complication is the synergy between gases. For example, it has been shown that SO_2 or H_2S alone are not very corrosive to silver or to copper, but the combination of these gases with other gases such as nitrogen dioxide (NO_2) and/or ozone (O_3) are very corrosive to copper and to silver (Volpe 1989). The effect of humidity is also complicated: the corrosion rate of copper is a strong function of relative humidity, while the corrosion rate of silver has less dependence on humidity (Rice et al. 1981).

A very convenient and quantitative way of determining the corrosivity of air is the so called "reactive monitoring" method described in the ANSI/ISA Standard 71.04-1985 standard (ISA 1985) and in ISO Standard 11844-2 (ISO 2005). The method exposes copper coupons to the environment for one month and analyzes the corrosion product thickness and chemistry using coulometric reduction to classify the environment into one of four severity levels. According to the ISA-71.04-1985 standard, the copper corrosion rate should be less than 300 Å/month for an environment sufficiently well controlled, such that corrosion will not be a factor determining equipment reliability (ISA 1985). But the use of copper coupon alone has two major limitations: (1) copper is not sensitive to chlorine, a contaminant particularly corrosive to many metals, (2) copper corrosion is overly sensitive to relative humidity. The inclusion of a silver coupon helps differentiate the corrosive contributions of gaseous contaminations and relative humidity. The ISO Standard 11844-2 (ISO 2005) and the ASHRAE white paper (ASHRAE 2011a) on data center contamination both include silver coupons along with copper coupons to gain greater insight into the chemistry of the corrosive gases in the environment.

The corrosion rate of copper and silver is measured in terms of the total thickness of the corrosion products in Å/month. The thickness of the corrosion products can potentially be measured by a variety of techniques:

- Specialized physical analysis techniques such as x-ray photoelectron spectroscopy (XPS) and SEM
- Electrochemical-based techniques, such as coulometric reduction
- Weight-gain method based on quartz microcrystal method
- Electrical method based on change of resistance of thin metal films

In the x-ray photoelectron spectroscopy (XPS) method, the sample is sputter etched for a short period and the chemistry of the surface is analyzed, followed by more sputter etching and chemical analysis. The process of etching and analysis is repeated until the elements associated with the corrosion products are no longer detected. At this point, the corrosion product has been sputtered through to the base metal. Knowing the rate of removal of the corrosion product and the time it took to remove the corrosion product, one can deduce the thickness of the corrosion product. For thicker corrosion product films, a more convenient method is of cross sectioning using standard metallographic practice or focused ion beam milling. The cross sections are examined in a SEM to measure the thickness of the corrosion products. XPS and SEMs are expensive and they do not lend themselves to a direct and convenient method of measuring the corrosion product thickness. They are useful for conducting fundamental corrosion research, but are not recommended for routine corrosion rate measurements.

The electrochemical technique of coulometeric reduction provides a very simple and convenient means of chemically identifying and measuring the thickness of the corrosion products on copper and silver foils. The technique refined by Krumbein (1989) has been used for many years and was the basis of the ASTM Standard B825-02 standard (ASTM 2008). The corrosion products on metal surfaces can be electrochemically reduced to metal by applying a cathodic current. The metal coupon under test is immersed in a deaerated 0.1 mol KCl electrolyte and its potential measured as a function of time while it is subjected to a constant cathodic current density typically equal to 0.050 mA/cm^2. The potential versus time plot has plateaus, one for each corrosion product that is reduced. From the coulombs associated with each corrosion product's plateau, the thickness of the corrosion product can be calculated. Coulometric reduction method has the advantage of being inexpensive and easy to run. The details of the technique using copper and silver coupons exposed to the environment for one month and analyzed using coulometric reduction are provided in Appendix A. Coulometric reduction services are commercially available.

Reactive monitoring using copper and silver coupons gives the average corrosion rate over the 30-day period the coupons are exposed to the data center environment. Any short-term variations in the gaseous contamination levels are missed. The shortcoming of the reactive monitoring method is overcome by the real-time, continuous monitoring of the environment that is possible using two commercially available devices: one based on a highly sensitive metal-plated quartz crystal microbalance (QCMs), the other based on measuring the change in resistance of metal thin films as corrosion reduces their thickness.

Quartz crystal microbalance (QCM) corrosion monitors are microprocessor-controlled devices that can measure the total environmental corrosion attributable to gaseous contaminants (Olsson and Landolt 2006). Commercially available monitors include copper- and silver-plated QCMs that can measure real-time changes in corrosion rates as a result of the changes in gaseous pollutant levels. QCMs measure corrosion rates as follows. When exposed to the environment, thin films of copper and silver, deposited on quartz crystals, corrode, gaining in mass. The mass gain is determined from the change in the resonant frequency of the QCM. With prior knowledge of the chemistry of the corrosion product and the density of the corrosion product, the rate of change of mass of the thin film can be converted to the rate of change of the corrosion product thickness in ångströms/month, as described in Appendix B.

Corrosion monitors can also be based on the rate of change of electrical resistance of thin metal films deposited in a serpentine pattern on silicon oxide or some other inert substrate. Knowing the chemistry and the physical properties of the corrosion products, the rate of change of resistance can be translated into the rate of change of thickness of the metal films and from that into corrosion rate in terms of the rate of increase of the corrosion product thickness in Å/month (ångströms/month) (Klein et al. 2011).

Reactive monitoring of gaseous contamination is complicated by the fact that metal corrosion rate is a function of the airflow over the corroding metal surface. The rate of corrosion rises with increasing air velocity until an air velocity is reached above which the corrosion rate plateaus. In a data center, the corrosion rates vary from location to location, being higher where the airflow velocity is higher. The most appropriate location for corrosion rate measurement to determine whether a data center air quality is acceptable is on the front face of the computer racks where the air enters the racks, at one-quarter and three-quarter height of the frame above the floor. The height at which the measurement should be done is somewhat arbitrary but necessary to specify for test standardization.

Real-time monitoring allows preventive measures to be taken immediately, such as shutting off the outdoor air from entering the data center should the outdoor air become too corrosive. A limitation of real-time monitoring is that it does not provide any information about the chemistry of the gaseous contamination. One has to know or assume the corrosion product chemistry in order to extract the corrosion rates from changes in mass, as in the case of the QCM method, and changes in resistance, as in the case of the resistivity method.

4.3 ACCEPTABLE LIMITS OF GASEOUS CONTAMINATION AND TEMPERATURE AND HUMIDITY

In mid-2010, a dozen members of ASHRAE TC 9.9 subcommittee representing the IT equipment manufacturers started a yearlong survey of data centers with and without corrosion-related hardware failures. The results of the survey are shown in Figures 4.4a and 4.4b. The silver corrosion rates in data centers that reported corrosion-related hardware failures were above about 200 Å/month, whereas those with no reported corrosion-related hardware failures had silver corrosion rates below about 200 Å/month. Copper corrosion rates, on the other hand, for data centers with and without corrosion-related hardware failures showed significant overlap, though in general the copper corrosion rates were higher in data centers with corrosion-related hardware failures. Based on this evidence, it may be concluded that the silver corrosion rate is a much better predictor of corrosion-related hardware failures and that datacom air quality should be improved to reduce the corrosion rate of silver to well below 200 Å/month to ensure that corrosion is not a factor determining hardware reliability.

The gaseous contamination levels in a data center are a function of location and time of year. The location of interest for gaseous corrosivity monitoring is approximately 5 cm (2 in.) in front of the rack on the air-inlet side, at one-quarter and three-quarter frame height off the floor. Ideally, monitoring should be done

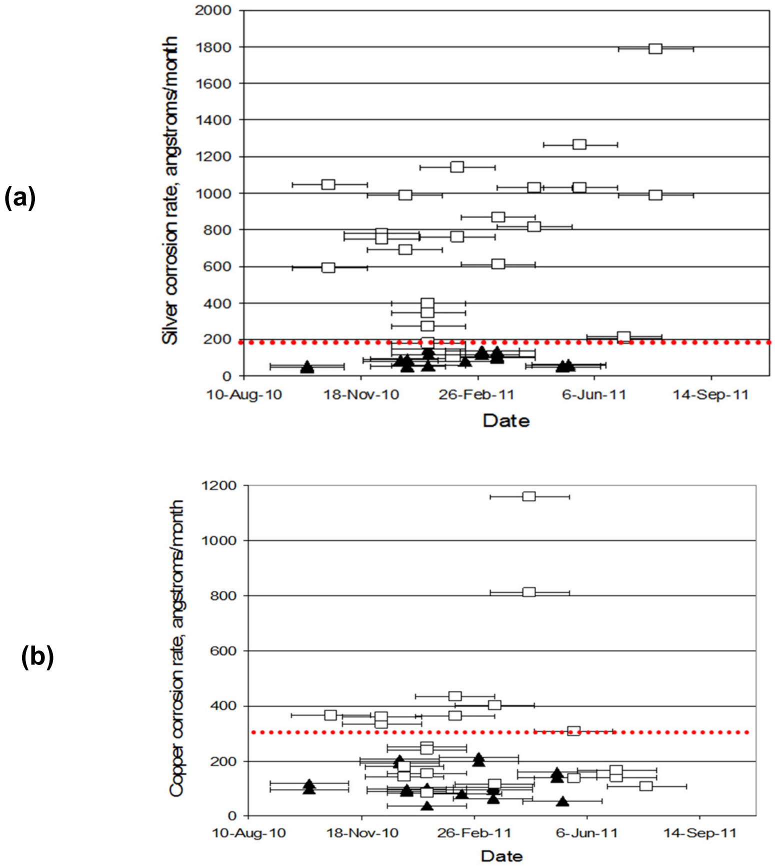


Figure 4.4 The square open data points are for data centers with known corrosion-related hardware failures. The triangular solid data points are for data centers with no known corrosion-related hardware failures. Note that the silver corrosion rates for data centers with and without corrosion-related hardware failures show no overlap, whereas the copper corrosion rates for the two types of data centers show significant overlap.

all year round, but as a data center's history builds up, monitoring may be limited to the months with known high levels of gaseous contamination. The reactive monitoring method requires the copper and the silver coupons be exposed for one month to get a good measure of the corrosivity of the environment. Data centers with air-side economizers have heightened reliability risk because of the greater possibility of the ingress of contaminated outdoor air. In data centers with air-side economizers supplemental real-time monitoring is recommended to enable quick reaction to outdoor events that may introduce corrosive gases into the data centers. Real-time monitoring is also recommended in data centers with gas-phase filtration air-cleaning systems in order to track the efficiency of the filters and to know when to change the filter media.

Figure 4.5 is an example of a corrosion monitor based on silver thin-film resistance change, tracking the corrosion rate on an hourly basis in a data center (Klein et al. 2011). Note the silver corrosion rate follows the outdoor SO_2 and NO_2 concentrations as reported by the local municipality. The silver corrosion rate is very low between noon and 8 p.m. and high (approximately 400Å/month) after 8 p.m. to next day noon. This example illustrates the power of real-time monitoring in helping to understand the source of the contamination. With real-time monitoring, changes in gaseous corrosivity can be detected quickly to allow preventive measures to be taken, such as shutting off outdoor corrosive air from entering the data center.

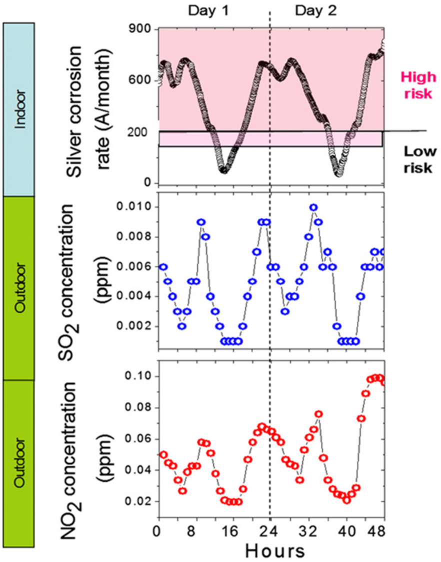


Figure 4.5 Silver corrosion rate in a data center as a function of time of day follows the outdoor SO_2 and NO_2 concentration levels.

5

Contamination Prevention

This chapter suggests ways to limit the concentrations of particulate and gaseous contamination to within acceptable limits through prevention and some control practices. Chapter 6 covers particulate and gaseous contamination control in more detail. Particulate and gaseous contaminations have the ability to degrade datacom equipment from the most basic electronic components to the most sophisticated information technology, infrastructure, and peripheral equipment. The datacom equipment contamination concerns and prevention methodologies discussed in this chapter apply to varying degrees to all datacom equipment and facilities. Not all facilities require the same level of contamination prevention. The economic effects of equipment downtime in an enterprise-level facility are presumably much more significant than the downtime economic effects of a point-of-sale server located within a retail store. The economic risks of equipment downtime attributed to particulate and gaseous contamination will drive which level of contamination prevention is required within any datacom equipment installation.

Potential contamination sources exist everywhere and are unavoidable in any building, structure, or datacom environment. Contaminants in the form of gases, solids, and liquids may be hazardous to IT and datacom equipment operation if not adequately considered and managed. In short, prevention and minimization of equipment-threatening contaminants is fundamental to the long-term reliability and availability of IT and datacom equipment. While there are many items to consider, strategies can be put in place to efficiently and effectively minimize the threat of most contaminants. Prior to design and construction, site selection is critical for the long-term survival of IT and datacom equipment. Some sites may require extra datacom center infrastructure and systems to manage environmental hazards. During the design and construction phase of a datacom equipment center, materials selection of everything from the raised-floor systems to the ceiling should be chosen to minimize the sources of contamination. Decisions of air pressurization and introduction of outdoor air must also be carefully made to achieve the goal of minimizing contaminants in the datacom environment. Infrastructure equipment selection, installation, maintenance, and physical placement of IT equipment all have an influence on the long-term cleanliness of the datacom environment. Operational strategies and policies must be clear, understood, and practiced by all datacom personnel and service providers. Even the best designed and constructed facility will become degraded if these policies are not included in the facility's standard operating procedure.

Prevention is the best way to limit the environmental and equipment contamination. Once contamination has entered the and datacom environment and the IT and datacom equipment, the expenditure to remove it can be significant in terms of service and labor costs or even larger when hardware replacement is necessary. The biggest contamination consequences are often the equipment downtime and lost revenue.

5.1 RISK ASSESSMENT

There are a multitude of potential contaminants and countless ways in which datacom equipment can be impacted. It is important to note that not all datacom equipment center environments are equally susceptible to all contaminants. Datacom operators need to realistically acknowledge when a datacom equipment center environment may be susceptible. For instance, two facilities of identical design and construction may be impacted differently simply because of different geographic locations. Conversely, two facilities in the same geographic area may be impacted differently because of facility design differences. A risk assessment should be conducted to characterize the contaminant potential. The results of the assessment should feed into other planning activities so that action plans can be developed to mitigate the impact of contamination-related risks.

5.2 FACILITY LOCATION

Datacom equipment center site selection, including identification of surrounding internal and external hazards, is an important consideration. When considering the location of a new or relocated datacom equipment center, the selection process should take into account contamination exposure risks from neighboring properties. These risks may include agricultural, chemical, biological, nuclear, and manufacturing processes, storage, and waste treatment operations. Facility location selectors also need to consider geographical locations that are prone to floods, tornadoes, volcanoes, or other acts of nature. Datacom equipment center contamination can also result from commercial transportation in proximity to the facility, such as heavy truck or train traffic and possibly airport operations with aircraft flight paths overhead. All of these sources of potential contaminants can put the datacom environment at risk. A completely risk-free datacom equipment center location is a rarity. Site selection usually involves compromises.

Protection from significant weather events, while costly, is an important consideration that involves both location and design. In flood-prone areas, it may be necessary to design all datacom equipment center areas with support equipment to be installed on upper floors in case the ground level floods. In areas prone to tornadoes and hurricanes, it may be important to properly orient the building and to adjust the facility design to survive high winds.

Even in nonstorm situations, the physical location of a building can significantly impact the level of contamination within the datacom equipment center. Particulate matter, airborne or otherwise outside a facility can and will find its way inside via cracks in the building, makeup air, and other exchanges with materials and people entering the datacom equipment center.

Urban areas contain man-made pollutants such as petrochemical materials from car tires, soot from combustion equipment, dust and debris from construction activity and so on. Rural datacom equipment center locations may experience more dust from loose soils and vegetation. Vacant lots and open spaces can suddenly become construction sites, exacerbating contamination problems. In both urban and rural settings, changes in wind direction and pressure will have an impact on the level of airborne particulate matter and the level of infiltration inside the datacom equipment center.

Typically, urban locations are more at risk for vibratory events, but both urban and rural locations are susceptible. Vibration can be caused by roadway traffic, trains, airplanes, and nearby construction. Vibration can cause various building components to shift and either dislodge particulate matter or create new particulate matter.

5.3 COMPUTER ROOM DESIGN

The datacom equipment center should be located within a building away from potential local hazards and physically separate from space continuously occupied by humans. For example, operations such as cafeterias or toilets located above or boiler rooms, steam pipes, or parking garages located adjacent to or below datacom environments can negatively affect the datacom equipment center environment contamination level, especially in the event of an accident, act of vandalism or terrorism.

The most effective method of dealing with contaminants is to keep them out of the datacom equipment center. Therefore, strict datacom equipment center practices should be established to minimize contaminants carried in by everyday occurrences. Absolutely no food or drink should be allowed in the datacom equipment center environment at any time. Crumbs from food or spilled liquids put datacom equipment at risk. Simply allowing food in the data center creates a careless attitude toward other contaminants. Cardboard boxes and IT equipment manuals should remain outside of the datacom equipment center in a designated location. Paper is another particulate source and is also a fuel source in the event of a fire. It is essential for facility owners and operators to designate an equipment unpacking and staging area to support moving of IT equipment. Tacky mats or contamination control mats should be installed just beyond the entrance(s) to the datacom equipment center to remove debris from shoes. There should be a set procedure for changing the mats so they remain effective.

Once a datacom equipment center facility location is finalized, the physical design of the datacom environment can impact the amount of particulate matter. Any opening can allow particulate matter into the facility, thus, the location of openings is important. Exterior windows should be avoided in the datacom equipment center not only to minimize the infiltration of contaminants but also to minimize security threats and solar gain. If the no exterior-windows guideline is impractical, windows should be located on the leeward side of the building, particularly in high-wind areas. Doorways to the datacom environment should be isolated from exterior doorways in an attempt to form an airlock. At no time should a building exterior door be open while the datacom equipment center entrance door is open. Positive pressurization by the use of conditioned makeup air, air showers, and vestibules are possible options for reducing the influx of contaminants.

5.3.1 Staging Areas

Areas outside the datacom environment should be provided to allow equipment to be delivered, unpacked, and staged prior to being installed in the datacom environment. Such an area allows equipment to be cleaned and prepared. It also enables crating and packing materials to be removed without contaminating the datacom environment. This area should be physically separate from the datacom environment, and air exchange should be prevented.

5.3.2 Storage Areas

Areas outside the datacom environment should be provided for the storage of spare parts, equipment, and supplies. Keep materials contaminated with particulate matter such as old computers, cable reels, cardboard boxes, paper, or other materials capable of generating particulate matter outside the datacom environment. It is also important to move parts and equipment through an area where they can be cleaned prior to being introduced into the datacom equipment center from storage.

5.3.3 Traffic Flow

The datacom environment should be designed for efficient foot traffic. Long delivery paths increase dirt pickup before equipment enters the datacom equipment center room. If equipment is covered with plastic during transport, the plastic should be removed before the equipment is taken into the datacom equipment center. Plastic accumulates particulate matter through electrostatic adhesion, the particulate matter can then be easily released into the environment of the datacom equipment center. Particulate matter can also be released into the room when plastic covering is agitated during the removal process. The wheels of transport devices should be rolled over tacky mats prior to entering the datacom equipment center. The datacom environment should be designed as a destination location within the facility structure, not a path or shortcut for people and materials to reach other locations.

5.3.4 Office and Operations Areas

A large quantity of particulate matter can be generated and transported by people. Limiting the number of people working in the datacom environment can effectively reduce contamination. All desks and work areas should be outside the datacom equipment center environment. The datacom equipment or network operations areas should be physically separate from the datacom environment and should be negatively pressurized relative to the datacom equipment center if there is a direct doorway path between them. Only those people who need to physically interact with the datacom equipment should be in the datacom equipment center.

5.4 COMPUTER ROOM CONSTRUCTION

Like most construction projects, a variety of materials are available for constructing a datacom equipment center. It is very easy to overlook the particulate matter characteristics of these materials. Generally, there are trade-offs between choosing materials with low potential of giving off particulate matter and other considerations such as safety and cost. When considering datacom equipment center construction consider the value of the computer hardware itself and the information stored in it. Contamination prevention is just as important a design consideration as power, cooling, and security.

5.4.1 Wall, Ceiling, Underfloor Materials, and Surfaces

Construction materials and surface finishes that are good from a particulate matter viewpoint are those that will give off no or comparatively little particulate matter. Such materials include metal, glass, and plastic. While these materials are used for various components, they are typically not used for wall, ceiling, or floor coverings because of cost and other limitations. Most datacom equipment center facilities are constructed utilizing concrete floors, gypsum board walls, cellulose suspended ceiling tiles, and sheet metal ducting. Unfortunately, each one of these materials generates significant particulate matter, particularly during datacom equipment center construction. Particulate matter will spread through the environment after material installation as the result of vibratory and abrasion events and airflow.

5.4.1.1 Underfloor Seal or Coating

Concrete is the workhorse of modern construction and is the base for most datacom environments. Concrete is also a potential source of contamination. Exposed concrete materials continually oxidize and the surface breaks down. Concrete surface breakdown creates loose contamination consisting of sand and lime particulate matter. Lime dust is particularly corrosive when dissolved in water or exposed to high humidity. Concrete surfaces must be protected against oxidation breakdown by sealing. Ideally, the seal is applied before the raised-access floor is installed, but a sealant can also be applied in an existing datacom facility. Select a water-based, volatile organic compound (VOC)-compliant sealer that is intended for datacom equipment center applications. Most new concrete materials are treated with a curing agent to help harden the concrete and produce a better surface. These curing agents are often called *surface sealers* but are predisposed to permeate into the concrete rather than remain on the surface as a surface protector.

A simple evaluation can be performed to determine the existence or condition of a concrete surface sealant. This is particularly useful for acceptance testing of a new datacom facility. To carry out this examination procedure, the examiner should put on laboratory glasses and gloves at a minimum. The following process should be used:

1. Use plain water to clean and remove any surface contamination over a 150 mm (6 in.) diameter area on the concrete surface to be evaluated.
2. Apply two to three drops of muriatic acid (HCI) on the concrete surface in the center of the circle.
3. If the muriatic acid remains on the concrete surface and looks like water, the concrete is adequately sealed for dust encapsulation purposes.
4. If the muriatic acid reacts with the concrete by producing clear or yellowish foam, the concrete is NOT adequately sealed. Do not breathe the vapor produced by the reaction.
5. Clean up the muriatic acid from the concrete surface test area, and properly dispose the hand protection gloves as well as the clean-up wipes.

NOTE: Muriatic acid is dangerous if not properly used. Do not apply more than two to three drops of acid on the concrete floor surface. Unsealed concrete and large quantities of acid will produce a vigorous reaction with dangerous amounts of fumes.

5.4.1.2 Wall Coverings

Most datacom equipment center environments are constructed using painted gypsum board partition walls. This is a material of choice provided the gypsum board surface is properly prepared and high-quality paint is applied. This will ensure that the surface will not chalk or rub off. Care must also be taken to ensure all cut gypsum board edges are properly covered or sealed (e.g., around holes cut for electrical and water inlets and outlets. Unused or abandoned holes and penetrations should be patched and painted.

Other types of wall construction and coverings have been used over the years. Porous surfaces such as fabric are not recommended, as they may capture and yield contaminants from the basic material. Such surfaces are also difficult to clean. All wall coverings and surface finishes must comply with applicable local building and fire codes.

5.4.1.3 Ceiling Tiles and Space

Ceiling tiles can be another significant contributor to datacom environment contamination. Most commercial lay-in ceiling panels are not suitable for use in datacom equipment center environments, since they are made from compressed cellulose and are highly friable, meaning that cellulose is easily broken into small fragments. Simple movements of the panels, either intentional or because of building vibration, can cause the edges of the panels to chip and break.

Acceptable panels are those with smooth surfaces that have wrapped or encapsulated edges. These types of panels are commonly used in food service kitchen and preparation areas. Just as the concrete in the underfloor space must be sealed to prevent surface oxidation and liberation of concrete dust into the airstream, any exposed concrete in the ceiling space must be sealed as well. Additionally, sprayed-on fire insulation, commonly used to protect structural steel, is a source of particulate matter and should be sealed if present in the ceiling space.

5.4.1.4 Zinc Whiskers

Besides metal shavings and rust particles, the most common electrically conductive contaminants found in a datacom equipment center environment are zinc whiskers. Zinc whisker growth has been documented on a broad range of zinc-coated datacom equipment and raised-access floor panels and support members. These include the underside of zinc-plated raised-access floor panels, support structures (pedestals and stringers), and associated mechanical assembly hardware. Wood core and concrete panels with flat steel bottoms are most susceptible. The steel surfaces may have been finished with zinc by using either an electroplating process or by using a hot-dip galvanization process for corrosion protection. Electroplated zinc typically has a uniformly dull gray appearance and is prone to zinc whisker formation and growth. Hot-dip galvanized steel typically has a spangled (glittery) or mottled (spotted) appearance similar to the finished surface of a tin bucket. Zinc whisker formation and growth have been frequently observed on electroplated zinc. Hot-dip galvanized is much less likely to form and grow zinc whiskers, and is therefore considered acceptable by the industry. Zinc whiskers, typically a micrometer in diameter and up to about 1 mm (0.04 in.) in length may dislodge from their sources, get into the datacom equipment through the equipment's air intake paths and result in electrical short circuiting in datacom equipment. While all exposed electronic circuitry is vulnerable, power supplies tend to fail in a dramatic fashion. Zinc whisker contamination may produce audible popping sounds when these whiskers arc across high-voltage conductors such as the leads of power metal oxide semiconductor field-effect transistors (MOSFETs).

It is important to recognize that almost all electroplated zinc surfaces are potential whisker sources. Zinc whiskers have been found on a wide range of products inside operating datacom environments, including the following:

- raised-access floor panels, pedestal, stringers, and pedestal heads
- steel building studs
- suspended ceiling T-grid components and hanger wires
- concealed-spline ceiling grid components
- thin wall electrical conduit
- datacom equipment racks and cabinets
- datacom equipment cases and enclosures

5.4.1.5 Tin Whiskers

Similar to zinc whiskers, tin whiskers are tiny, electrically conductive, pure-metal, hair-like crystalline structures that grow from tin electroplated surfaces. Tin whiskers can grow in abundance and cause bridging and electrical shorting of electrical conductors as well as component leads and terminations. Exposed leads on electronic components are commonly plated with tin or tin-lead alloys to prevent corrosion and to enhance solderability. More and more manufacturers are complying with the European Union directive 2002/95/EC on the "restriction of the use of certain hazardous substances in electrical and electronic equipment," or RoHS (RoHS 2003), by removing lead metal from their plating formulations. Today, many lead-free electronic component terminations are plated using a pure-tin plating process. Pure-tin plating is a common source of whisker growth. There have been many documented findings of tin whisker growth on electronic components that has caused failures of the datacom equipment. A good source of whisker information can be found at the U.S. National Aeronautics and Space Administration (NASA) Web site, http://nepp.nasa.gov/whisker/.

Tin and zinc whisker growth mechanisms are not well understood. Many component manufacturers and plating industry professionals have developed effective ways to work around them by modifying the plating metallurgies: for example, it is now well known that nickel underplate prevents tin whisker formation. Alloyed metals tend to be less susceptible to whisker growth.

5.4.2 Fit and Finish

Improperly fitted and finished interior systems can contribute to contamination in the datacom equipment centers. The amount of air moving through building cracks can be significant. With the unwanted airflow comes contamination either from outside the building or from contaminated areas within the building. This is one reason datacom equipment centers should be positively pressurized relative to the surrounding areas. Although not the focus of this publication, such cracks and associated air leaks reduce operational efficiency by bleeding conditioned air from the datacom equipment center and therefore are covered generally here.

Areas of significant concern include the following:

- Ceiling panels should be sized to fit snugly at the sides and ends within the grid. Broken or chipped panels will allow the exterior building air to infiltrate the datacom center.
- Gypsum boards should be adequately caulked to the slab (at the base) and to the roof or slab of the adjacent floor. Consideration should be given to building movement and expansion as well as to fire rating when selecting material and caulk.
- Hollow columns can generate significant amounts of airflow because of the chimney effect. This airflow can carry contaminants into the datacom equipment center. Figure 5.1 shows a common occurrence where a large opening is created to facilitate the utility installation and is never repaired.

5.4.3 HVAC System

The datacom equipment center HVAC system can be considered part of the datacom equipment center room construction. The HVAC system can be a significant source of both particulate matter and gaseous contamination.

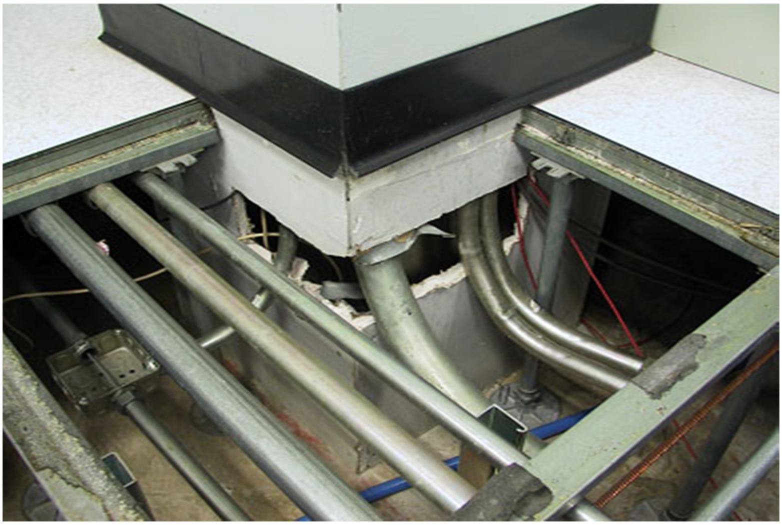


Figure 5.1 Hollow column with a large hole.

5.4.4 Makeup Air

Fresh makeup air is a building code requirement for installations with human occupants. The typical commercial HVAC installation has minimal filtration of the outdoor air before it is mixed into the return airstream, conditioned, and supplied back into the environment. It is not unusual for the same equipment design to be used for the datacom equipment center environment makeup air system. However, if datacom environmental HVAC systems do not properly filter the outdoor air, the datacom equipment could become contaminated with the outdoor air pollutants. Lack of adequate filtration can be disastrous to datacom and infrastructure equipment if the outdoor air is heavily polluted. Countries with lax pollution standards are more at risk when using makeup air. Local or regional authoritative sources should be sought for up-to-date information about outdoor ambient conditions. For example, the U.S. Environmental Protection Agency (EPA) has a web site that produces reports and maps of air pollution for any locale within the U.S. (www.epa.gov/airdata/) (EPA 2014). Also, the U.S. Federal Emergency Management Agency (FEMA) has a Mapping Information Platform that can provide hazard information with respect to volcanoes, forest fires, and wind storms (FEMA 2014).

5.4.5 Positive Pressurization

Positive pressurization helps prevent contaminated air from entering the datacom equipment center environment. This can be achieved by pressurizing the room to 13 to 25 Pa (0.05 to 0.1 in. of water) by introducing outdoor (ventilation) air at a rate of 3 to 6 air changes per hour (ach) (5% to 10% of the gross room volume per minute). The use of positive pressurization with outdoor air not only keeps particulate contaminants out of the datacom equipment center, but it is also used to prevent corrosive gases and VOCs from entering the data center (Krzyzanowski and Reagor 1991). Any air entering the datacom equipment center should be conditioned and filtered to ensure that datacom equipment temperature, humidity, and cleanliness stay within the datacom equipment specifications.

5.4.6 Humidification Systems

Thermal Guidelines for Data Processing Environments, Third Edition (ASHRAE 2012c) has updated the allowable environmental temperature and humidity envelopes to enable some facility operators to design data centers that use substantially less energy to cool. The recommended temperature and humidity envelope remains unchanged: the lower- and upper-bound dew points are 5.5°C (42°F) and 15°C (59°F), with the dry-bulb temperature in the range of 18°C to 27°C and relative humidity less than 60% (see Figure 5.2). Most facilities achieve the necessary humidification through specialty humidifiers. See Chapter 22 of the 2012 *ASHRAE Handbook—HVAC Systems and Equipment* (ASHRAE 2012b) to see the range of equipment types available. While several technologies exist, all of them have trades-offs between water quality, maintenance, and contamination. Because standard tap water is rarely suitable for use in humidification systems, care is required in matching the water quality and associated treatment equipment to the selected humidifier. Water contains particles, bacteria, dissolved solids, and a wide range of chemicals. These impurities can affect the humidification system and its performance. Many of the impurities in the water can contaminate the datacom center environment.

There are four categories of water to consider for use in humidifiers:

1. Potable water essentially has no treatment other than filtration. Unless the potable water source has very low dissolved solids, this source will significantly increase maintenance and repair costs and may contaminate the data center with particulate matter.
2. Softened water may not be appropriate for humidification if its sodium ion content is too high. Water softeners depend on an ion-exchange resin in which "hardness ions" in the water, mainly Ca++ and Mg++, are exchanged for Na+ ions. Ion exchange devices do not reduce the cation content in the water, they merely replace the Ca++ and Mg++ ions in the water with Na+ ions. Depending on the amount of calcium and magnesium ions in the water being softened, the concentration of sodium ions in the softened water may be too high for use in humidifiers.

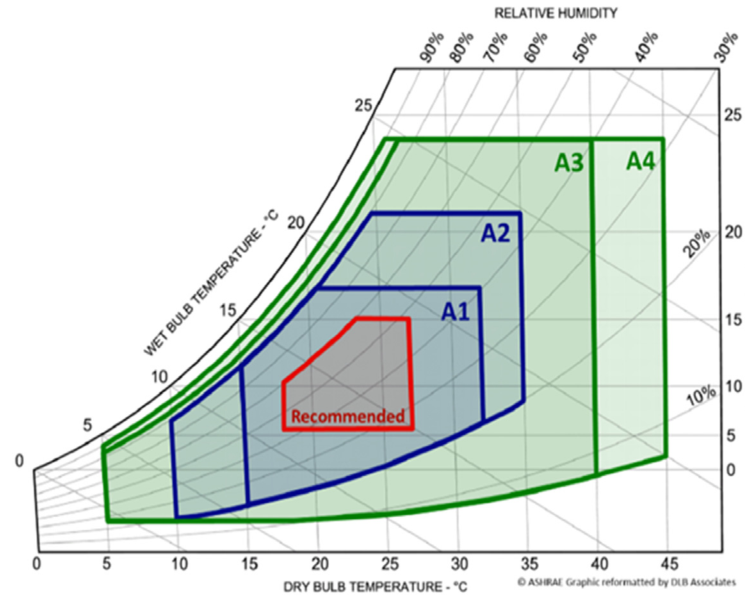


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Figure 5.2 ASHRAE thermal guidelines for data processing environments

3. Reverse osmosis removes a majority of water borne contaminants by using a semipermeable membrane. The water is pressurized to overcome the osmotic pressure of the membrane. The result is that contaminants in the water stay on the pressurized side and pure water permeates into the other, low pressure side. Reverse osmosis is capable of rejecting the majority of contaminants and will provide suitable feed water to the humidifier. Reverse osmosis results in a minimum of humidifier maintenance and cleaning.
4. Deionization removes both anions and cations, providing a high-purity water stream. Deionization systems are typically the most complex but will provide the highest water quality. Very pure deionized water becomes a corrosive fluid when it absorbs carbon dioxide from the air. The humidification supplier should be consulted about material compatibility if deionized water is used.

The extent of water conversion to steam or water vapor should be looked at carefully. If the system generates a water mist, the size of the droplets and the ability of the HVAC system to fully evaporate them before entering the IT equipment are critical. A humidifier that generates a fine spray may create undesired airborne contaminants, especially if the water has a significant quantity of dissolved solids or particulate matter.

The sizing of the reverse osmosis, or deionization system is dependent on both the water flow rate and the amount of total dissolved solids in the feed water. The specific manufacturer's guidance should be followed.

This book specifically does not cover the issue of personal health and comfort associated with biological contamination in the humidifier. See Chapter 22 of *ASHRAE Handbook—HVAC Systems and Equipment* (ASHRAE 2012b) for further reference and guidance. Unfortunately, the purification processes may actually remove the bacterial control chemistry, and as such, the system design may need the review of appropriate environmental hygiene experts.

Humidity can impact the rate of corrosion in the datacom environment. In general, ion migration, deliquescence of hydroscopic salts, and/or condensation can occur on computer components if the humidity level is too high.

Humidity control can be challenging in air-side economizer installations. External ambient humidity considerations should be included when designing humidification control for these facilities.

5.4.7 Air Filtration

Filtration is an integral part of any air movement device that may be part of the equipment, added to an existing system, or a stand-alone unit. Filtering may take place in recirculated air using the computer room air-conditioning (CRAC) units, in makeup air supplied from the outdoor environment, and in some datacom equipment.

Since gaseous and particulate contamination control is a major issue in data center design, Chapter 6 is solely devoted to this topic.

5.4.8 Fire Suppression System

The most commonly used fire suppression systems for datacom equipment center environments are the following:

- Water based: sprinklers (NFPA 2007) and mist suppression (NFPA 2006)
- Gaseous based: clean-agent gas suppression (NFPA 2008) and halon gas suppression (NFPA 2009)

Foams, dry and wet chemical agents, and inert gases are less commonly found in datacom equipment centers, therefore, their effect on computer equipment is not considered. Clean-agent and halon-type suppression systems do not have a negative impact on computer equipment. However, fire suppression systems should be evaluated to determine if the agents themselves, in the event of an accidental discharge, or the by-products that form when exposed to excessive heat or fire can harm the computer equipment.

5.4.9 Mechanical Malfunction

CRACs and computer room air handlers (CRAHs) can produce contamination internally in the datacom center. Blower and motor pulleys can become misaligned, causing the rapid deterioration of the belts and pulleys. The belt and pulley wear produce debris that can contaminate the datacom center.

There are three primary causes of excessive drive belt wear: the belt design and materials, belt and pulley alignment, and the belt tension. Stack and Fannin (2010), reviewed three original equipment manufacturers' (OEM) drive belts. It was shown that raw-edge belt design performed better than the seamless design. The wrap-molded belt also performed better than the seamless, but not as well as the raw-edge belt. The study indicates that when non-OEM drive belts are used as OEM replacements, these belts have significantly shorter lives due to excessive wear and stretching. It is recommended that OEM drive belt replacements be used because they are usually designed and dimensioned to match as a set of two or three for uniform belt tension.

Proper drive belt alignment is also critical. Proper alignment means the belt is positioned exactly 90 degrees to the motor and blower shafts. Drive belt misalignment will cause side loading on the belt or imbalance between paired belts if more than one belt is used, both of which result in excessive belt heating. The alignment of the belt is impacted not only by the original factory design but also by adjustments made in the field to vary the blower speed. This is especially true if variable-pitch pulleys are used. As a variable-pitch pulley is adjusted, the center distance between the pulleys is changed as well as the center line of the pulley. That is because one side of the pulley is fixed in place while the other side is moved in and out to adjust how far the belt drops into the pulley groove. If possible, variable-pitch pulleys should be changed to fixed dimension units once the desired dimension is known in the field. In addition, as the system runs, the drive belt heats up. The heat can cause the drive belt to lose tension, stretch, and slip if the center distance of the pulleys are not properly adjusted. Once a belt begins to slip, it heats up faster, causing more slip and wear.

The heat also causes the drive belt to harden. This results in belt cracking and loose particle generation. Filters in the CRAC and CRAH units do not filter the particulate matter because the belts and pulleys producing the wear are downstream of the filters. Drive belts and pulleys must be maintained and precisely aligned at all times. The use of variable-frequency drives or electronically commutated motors may eliminate the use of drive belts and associated particulate matter contamination.

5.4.10 Ceiling Returns

Historically, datacom equipment centers were designed as typical office environments. Suspended ceilings were installed to enclose unsightly mechanical systems and to provide a pleasing aesthetic appearance. To respond to cooling challenges, many new datacom environments are constructed without suspended ceilings. This design approach allows hot air to rise farther away from the datacom equipment on its return back to the cooling equipment. A number of datacom equipment center owners are simulating this airflow pattern by taking advantage of the ceiling space above the suspended tiles. This approach is done by installing open diffusers over hot aisles and then ducting the hot air from the ceiling space back to the cooling unit intakes.

This airflow implementation presents new challenges for controlling contaminants. The ceiling space is now an active airflow return area and is subjected to contamination accumulation. Active airflow returns collect particulate matter contamination and require periodic cleaning to limit their impact on the environment. Cleaning the ceiling space can be a difficult procedure due to the nature of the area, difficulty of access, and density of components and surfaces on which contamination can accumulate. Finally, extreme caution must be exercised when cleaning this space, since it is directly over active IT and datacom equipment.

5.5 OPERATIONAL PROCEDURES

After a datacom equipment center facility is designed and constructed, there are a variety of operational procedures that should be adopted to assist datacom operators in preventing the entry and impact of contamination within the datacom equipment center environment.

5.5.1 Record Keeping

Record keeping may seem like a simple task, but keeping track of various datacom equipment center activities in and around the datacom environment will provide the foundation for many decisions. Most management decisions are based on data. Without data, decisions are random and unreliable. The ability to identify the impact of various activities is important. Frequently, there is a direct correlation among a number of activities in or around a datacom equipment center and contamination-related problems.

It is crucial that equipment anomalies and failures are recorded. Subtleties and trends can only be detected if there are recorded data to analyze. Too often, datacom operators disregard failures as random events and neglect to record the event because of the failure's limited effect. In reality, the failure may be part of a larger failure trend that could have been detected if the records had been updated and maintained.

5.5.2 Control Access

Datacom workers are another source and contributor of particulate matter within the datacom equipment center. Limiting the number of people entering the datacom equipment center is an excellent way to limit the particulate matter contributed by them. The following steps should be considered to reduce the number of people in the datacom equipment center:

- Install a datacom equipment center access control system for physical admittance into the space. Numerous people access the datacom equipment center simply because they are unrestricted.
- Access should be restricted to those individuals, facility maintenance personnel, and service providers necessary to support the datacom equipment and environmental infrastructure.
- Periodically review access security control records to ensure that only those people who are required for datacom equipment center operations are granted access. It is not uncommon for employees and service providers to remain on approved access lists long after their assignment has changed or access is no longer required.
- Review service and work processes and change procedures to allow only those tasks absolutely necessary to be conducted inside the datacom equipment center. Many tasks that historically required physical interaction with the equipment can now be accomplished remotely. Encourage staff to interact with and manage systems remotely.
- Consider strategically locating datacom equipment and people within the datacom equipment center to a concentrated area. By grouping such activities and equipment, the need for people to move throughout the datacom

equipment center is greatly reduced. The concentrated area should be located as far as possible from the most sensitive datacom equipment.

- Establish an access control audit team and ensure that their requirements are addressed in the design process.

5.5.3 Track-Off Matting and Contamination Control Mats

People and materials represent a noteworthy contributor of particulate matter in the datacom environment. People track particulate matter on clothing, footwear, and portable equipment. The majority of materials are wheeled into the datacom equipment center on carts, dollies, or hand trucks. A combination of track-off matting and contamination control mats (tacky mats) can significantly reduce particulate matter from people and materials.

Track-off mats are typically constructed using man-made fibers affixed to a rubber backing. These mats are commonly placed inside doorways to remove soil and to absorb moisture from footwear. Track-off mats with different fiber densities and naps are available for a large assortment of contaminant conditions. Track-off mats require maintenance and can be serviced and reused. When servicing mats, the product manufacturer's recommended procedures should be followed. Professional service companies offer contamination mat rentals that include periodic exchange and other contamination control cleaning services.

Contamination control mats, also known as *tacky mats* or *sticky mats*, are available as both renewable and disposable products. Both tacky and sticky mats feature a mildly sticky surface that captures contaminants that are lightly bound to the host's contact surface (e.g., dust on footwear and moving cart wheels). Typically, renewable matting is permanently glued down. Vacuuming and damp-mopping the surface on a daily or more frequent basis renews the surface. Disposable mats are constructed using multiple layers of thin adhesive plastic sheets. When the exposed layer becomes soiled, it is peeled away and discarded to expose a fresh layer. Effective decontamination needs at least six footfalls, three for each foot or three full wheel rotations. Using an average person's walking stride, the matting length required is approximately 4.6 m (15 ft). Ideally, this distance would be applied to all contamination control mats. In practice, this is not always possible due to space constraints.

5.5.4 Datacom Equipment Center Change Control

Many datacom equipment center disasters have been caused by poorly planned or poorly timed datacom activities. Adopting and enforcing change control processes and logically questioning all aspects of the internal procedures can help ensure that maintenance activities are reviewed and evaluated for potential datacom equipment center impacts. For instance, what are the particulate risks connected to using a ladder to open a ceiling tile above a datacom equipment rack?

What additional contamination risks are associated with the type of work that will be done above the ceiling? Who in the datacom equipment center organization will assess the risk of the contamination that may be produced around the rack? Who will be notified if a problem occurs? These are the kind of questions that should be answered and resolved before any datacom equipment center change activity is allowed to proceed.

6

Contamination Control

The European Union (EU) directive 2002/95/EC on the Restriction of the use of certain Hazardous Substances in electrical and electronic equipment, or RoHS, was implemented in July 2006 (RoHS 2003). However, this was only the first of many such regulations that have been passed or are being considered in many countries. There are now more than a dozen countries with regulations that affect everything from consumer electronics to industrial process and control systems. All these environmental initiatives place limits on or eliminate heavy metals, chemicals, and other environmental pollutants used in the manufacture of various types of electronic and electric equipment that have been linked to lasting environmental impacts and to human health effects. The aim shared by almost all the RoHS legislations is the elimination of lead metal used in solders and plating. These policies are now generally referred to as the RoHS Directive and are often referred to as "Lead-Free" legislation.

Datacom and IT equipment are at risk in locations with poor ambient air quality. PCBs assembled using lead-free solders can be more susceptible to corrosion than their tin-lead counterparts, and it has been reported that many lead-free circuit boards will suffer creep corrosion in operating environments high in sulfur-bearing gaseous contamination. Creep corrosion failures have occurred on hard disk drives, graphic cards, memory cards, and motherboards in desktop and workstation systems.

Corrosion-induced failures are frequent in electronics products used in industrial environments. However, now even in environments previously considered benign, IT equipment is experiencing serious corrosion problems as a direct result of RoHS compliance. Data centers in many urban locations have reported failures of servers and hard disk drives due to corrosion caused by sulfur-bearing gaseous contamination (Crosley et al. 2009). Desktop and laptop computers, servers, IT and datacom equipment are now at risk because of their RoHS-compliant design.

Acidic gases and fine particulate matter are typically found in urban environments from automobile and diesel exhaust, emissions from other forms of transportation, heat and power generation, and industrial activity. Sulfur oxides, active sulfur compounds, and inorganic chlorides are the primary offenders corroding electronic components. Additionally, oxides of nitrogen produced from the combustion process in automobiles, trucks, buses, and trains can act synergistically with sulfur-bearing gases to corrode electronic hardware. Although most computer rooms in commercial buildings are typically protected against out-of-specification temperature and humidity variations, particulates and acidic (corrosive) gases can be drawn in through the building's air-handling system and cause electronic hardware to corrode, especially if it was manufactured since the passage of various lead-free regulations.

The new industry-accepted specifications for contamination now include particulate contamination limits specifying the quantity and the deliquescent relative humidity of dust. Additionally, research by ASHRAE Technical Committee 9.9 led to the publication of a white paper on contamination guidelines for data centers (ASHRAE 2011a) and the formulation of new gaseous contamination limits used to update ANSI/ISA Standard 71.04-2013 (ISA 2013). This research also led to the publication of an iNEMI position paper (iNEMI 2012) on gaseous contamination as well as current efforts to update the Chinese National Standard GB 50174-2008, "Code for Design of Electronic Information System Room" to include gaseous contamination limits (China Electronics Engineering Design Institute 2008).

With the changes to IT and datacom equipment mandated by various RoHS directives, data center owners, managers, and operators should include an environmental contamination monitoring and control section as part of an overall site planning, risk management, mitigation, and an improvement plan. The plan should consist of the following:

1. **Considerations for the assessment of the outdoor and indoor air with respect to corrosion potential:** ANSI/ISA Standard 71.04-2013 can be used to provide site-specific data on the types and levels of gaseous contamination in terms of the amounts and type of corrosion products being formed (ISA 2013). Corrosion classification coupons (CCCs) can be used as a survey tool to establish baseline data necessary to determine if and what type of environmental controls are needed.
2. **Development and specification of a specific contamination control strategy:** Corrosion in an indoor environment is most often caused by a short list of chemical contaminants or a combination of contaminants. The contaminants present in a specific area are highly dependent on the controls put in place to mitigate them. The mitigation strategy should include the selection and application of an appropriate chemical filtration system to clean both the outdoor air being used for pressurization and/or ventilation as well as any recirculation air.
3. **Establishing a real-time environmental monitoring program based on the severity levels established in ANSI/ISA Standard 71.04-2013:** Real-time atmospheric corrosion monitors can provide accurate and timely data on the performance of the chemical filtration systems as well as the room air quality.

The absence of contamination controls in data centers is often the result of a lack of understanding of the relationship between air corrosivity and hardware failure rates. The continuing efforts by the leading datacom and IT companies are helping shrink this knowledge gap. Successful corrosion monitoring and control programs are being developed and implemented, assuring reliable operation of IT and datacom equipment.

6.1 AIR MONITORING

Air monitoring is the first step in the control of airborne contamination. Evaluating and recording the condition of the datacom environment is paramount in the determination of whether existing prevention and control activities are adequate and effective.

6.1.1 Particulate Monitoring

Visual observations and physical inspections are the least expensive monitoring techniques. Examination of surfaces in the datacom equipment center room where particulate matter may accumulate, especially in hard-to-reach places can provide a good idea of air cleanliness. Close inspection of air-handling equipment and manufacturer-supplied filters and the air-inlet paths within the datacom equipment center can provide details of where and how particulate matter is being introduced. If the datacom equipment has a suspended ceiling, ceiling tiles should be removed and the topsides visually inspected for particulate matter. When datacom or facility work, such as equipment installation, facility maintenance, renovation, etc., is completed, it is imperative that the work areas be inspected for dirt, dust, wire clippings, metal shavings, etc., and if found, these contaminations should be removed. If particulate matter appears suddenly or is observed to accumulate quickly, there is reason to investigate. Unexpected accumulation of particulate matter can often lead to equipment failure or the breakdown of a control or separation barrier. Both occurrences are serious and should be corrected. Appropriate response and correction are necessary to limit the degrading effects that particulate matter have on hardware reliability.

Monitoring of particulate matter is an ongoing process. Direct, continuous monitoring of air quality can be easily performed by on-site personnel. Instituting real-time particulate matter monitoring can establish a particulate matter baseline for the space, assist in the identification of potential sources, and provide assurance that any mitigation actions up to and including the use of air cleaning is working properly. Portable particle counters are available that are fairly inexpensive, straightforward to use, and can be used to perform periodic scans of the data center to verify compliance with particulate matter specifications. Today, particle counters are used to continuously improve productivity by providing detailed information on particle contamination levels, trends, and sources. Data center owners and operators can use particle counter data to understand causes of contamination, precisely schedule maintenance cycles, correlate contamination levels with equipment reliability issues, and fine-tune particulate matter control strategies.

6.1.2 Gaseous Contamination (Reactivity) Monitoring

A simple quantitative method to determine the air corrosivity in a data center environment is by reactivity monitoring, as described in ANSI/ISA Standard 71.04-2013, *Environmental Conditions for Process Measurement and Control Systems: Airborne Contaminants* (ISA 2013). Copper and silver coupons (metal foils) are exposed to the environment for a period of time, typically a month, and the thickness and the chemistry of the corrosion products are determined. Both copper and silver reactivity monitoring is now required as part of an environmental assessment in order to provide a complete accounting of the chemistry of the gaseous contaminants in the data center environment.

As described in Table 6.1, ANSI/ISA Standard 71.04-2103 classifies four levels of environmental severity for electrical and electronic systems providing a measure of the corrosion potential of an environment (ISA 2013). The overall classification is based on the higher of the copper and silver reactivity rates.

Corrosion classification coupons, described in detail in Chapter 4, are typically used for assessing the air corrosivity in data centers. Used on a continuing basis, they can provide historical data and establish environmental baselines. Air corrosivity monitoring is especially important where IT equipment warranties specify establishing and maintaining an ISA Class G1 environment. For equipment warranty, the concern is the that the quality of the air entering the equipment may not be within ISA class G1 severity level. The air quality in the rest of the data center is irrelevant to the warranty issue, though it is important from a contamination control point of

Table 6.1 Classification of Reactive Environments

Class	Severity Level	Copper Reactivity, Å/month	Silver Reactivity, Å/month	Comments
G1	Mild	<300	<200	Corrosion is not a factor in determining equipment reliability.
G2	Moderate	<1000	<1000	Corrosion effects are measurable and corrosion may be a factor.
G3	Harsh	<2000	<2000	High probability that corrosive attack will occur.
GX	Severe	≥2000	≥2000	Only specially designed and packaged equipment expected to survive.

Source: ANSI/ISA Standard 71.04-2013 (ISA 2013).

view. Air quality is seasonal and therefore should be assessed at regular intervals during the year.

In addition to corrosion classification coupons, real-time corrosion monitors may be used to provide continuous corrosion rate information needed to assess the effectiveness of the contamination control system.

Where corrosion problems have been identified, it is recommended to place atmospheric corrosion monitors in a number of locations in order to determine if contamination is widespread or limited to a specific area. Once a baseline had been established, some of the monitors could be later redeployed around the problem area(s) to gage the effectiveness of contamination control strategies that may have been implemented. Once the data center environment is under control and meets the conditions set forth in the manufacturers' warranties, one can determine the best permanent atmospheric corrosion monitoring locations for specific needs. As already mentioned, the manufacturers' warranties will require the air entering the IT equipment to be monitored.

6.2 CONTAMINATION CONTROL

Enhanced air cleaning is increasingly being used in data centers to provide and maintain acceptable air quality. Using the proper air filtration technology can effectively reduce airborne contaminants to well below specified levels and minimize equipment failure rates. Air-cleaning strategies must be optimized for both particulate and gaseous contamination removal.

Particulate filtration is a mature technology that is relatively easy to implement (Muller and Jin 2009). Gaseous contamination control technology is not as well established and is not as easily applied. Most computer room air-ducting systems and CRACs are not designed to readily accommodate gas phase filtration.

For many years, packed-bed, 25 to 75 mm (1 to 3 in.) thick, gas phase air filters employing one or more granular adsorbent materials, used in combination with particulate filters, have proven to be very effective for the control of pollutants (Figure 6.1). This combination allows for the maximization of both particulate and gaseous pollutant control within the same system. Common gaseous adsorbents include granular activated carbon (GAC), permanganate-impregnated alumina (PIA), and other manufactured media. These media are used individually or as blends to provide control of many common gaseous pollutants such as sulfur and nitrogen oxides, hydrogen sulfide, chlorine, ozone, formaldehyde, ammonia, toluene, and many volatile organic compounds (VOCs).

To maintain a high level of equipment reliability, it should be understood that a data center is a dynamic environment where many maintenance operations, infrastructure upgrades, and equipment change activities occur on a regular basis. Airborne contaminants that are harmful to sensitive electronic devices can be introduced into the operating environment from external sources through the ventilation

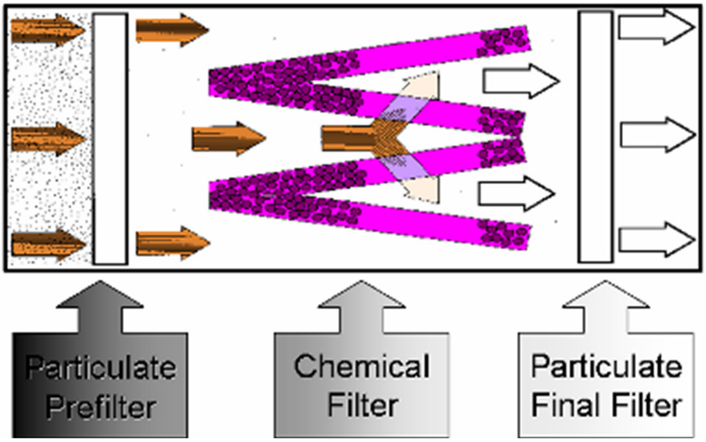

Figure 6.1 Schematic of an enhanced air cleaning system.

system. However, there are also potential sources of contaminations inside the data center itself, such as chlorine that can be emitted from the PVC insulation used on wires and cables if temperatures inside the server cabinets get too high.

Nonetheless, outdoor air being used for ventilation, pressurization and/or cooling remains the primary source of airborne contaminants, and this air should be cleaned before it is introduced into the data center environment. With the ever-increasing priority to reduce energy consumption in data centers, and the growing interest in the use of air-side economizers for free-air cooling, even data centers located in regions without major air quality concerns may struggle to maintain an environment favorable to the protection of sensitive electronic equipment.

There is no single, harmonized standard for data center design. One or more of several different technologies may be required depending on whether the air-handling system uses outdoor air to provide for ventilation, pressurization, and/or free-air cooling, or whether the CRAC units are used as 100% recirculating air systems.

The optimum control of airborne pollutants would allow for separate air-cleaning sections for particulate and gaseous contaminant control in the mechanical air-handling system. If this is not practical from a logistical or cost standpoint, air cleaning may be integrated directly into the fresh air systems or CRAC units or applied as stand-alone systems. Again, because most of these air-handling systems already have particulate filtration as part of their standard design, it is possible to add gas phase filters to these units without much effort. However, the manufacturers of the CRAC units must be consulted to determine what limitations there might in terms of the additional static pressure drop across these filters.

The following sections will describe some basic steps for the application and optimization of enhanced air cleaning for the data center environment.

6.2.1 Basic Data Center Design Requirements

As a result of the changes in warranty requirements for new IT and datacom equipment, data center owners and operators must address some basic design requirements to ensure that they are meeting manufacturers' specifications for air quality. This is especially important before one considers adding enhanced air cleaning for either particulate and/or gas phase contamination. Specific mechanical design and environmental requirements that must be considered include the following:

- Room air pressurization
- Room air recirculation
- Humidity control
- Temperature control
- Proper sealing of the critical spaces

Room air pressurization with clean air: To prevent contaminated outdoor air from entering the data center, all critical areas must be maintained at a slightly positive pressure relative to the outside pressure. This can be achieved by pressurizing the room to 13 to 25 Pa (0.05 to 0.1 in. of water) by introducing outdoor (ventilation) air at a rate of 3 to 6 air changes per hour (ach) (5 to 10% of the gross room volume per minute).

Room air recirculation cleaning: Air-cleaning systems can be designed to function as pressurization-only systems or as pressurization and recirculation systems. Pressurization with clean air may be sufficient to provide an acceptable level of contamination control but is dependent on how well the data center environment is sealed, on the level of pedestrian traffic into and out of the space, and on the level of other internally-generated contaminants.

Cleaning of room-recirculated air may be required if the following conditions are present:

1. The room is not properly sealed.
2. The space has high pedestrian traffic.
3. Internally-generated contaminant control is not practical.
4. The CRAC units or negative pressure ductwork are located outside the data center environment.
5. One or more of the walls of the data center are outside walls.

Typical recommended room air change rates are 6 to 12 ach (approximately 10% to 20% of the gross room volume per minute).

Temperature and humidity control: The corrosion potential of any environment increases dramatically with increasing relative humidity. Rapid changes in temperature and relative humidity can result in localized areas of condensation and, ultimately, in corrosive failure. The relative humidity should be maintained at the lowest practical level with specific consideration given to the risk of electrostatic damage (ESD) to delicate electronic components. The ASHRAE TC 9.9 publication *Thermal Guidelines for Data Processing Environments—Expanded Data Center Classes and Usage Guidance* (ASHRAE 2011b) extended the temperature-humidity envelope to provide greater flexibility in data center facility operations, particularly with the goals of maintaining high reliability and operating data centers in the most energy efficient manner. These guidelines have been agreed to by all major IT manufacturers. However, one downside of expanding the temperature-humidity envelope is the increased reliability risk from higher levels of gaseous and particulate contamination entering the data center, especially for data centers using outdoor air for free-air cooling with air-side economizers.

Proper sealing of protected spaces: Without a tightly sealed room, it will be very difficult to control the four points mentioned above: room air pressurization, room air recirculation, temperature, and humidity. It is essential that the critical spaces be protected by proper sealing. Actions taken to accomplish this include the use of airlock entries/exits, sealing around doors and windows, the use of door sweeps, the closing and sealing of all holes, cracks, wall and ceiling joints, and cable and utility penetrations. Care should be taken to ensure that any space above a drop ceiling or below a raised floor is sealed properly.

6.2.2 Particulate Contamination Control

It is important that the air handlers have the appropriate particulate filters to ensure meeting the ISA Class 8 cleanliness described in Table 3.3.

In-room process cooling with recirculation is the recommended method of controlling the data center environment. Air from the IT equipment areas is passed through the CRAC units where it is filtered and cooled, and then introduced into the subfloor plenum. The plenum is pressurized, and the conditioned air is forced into the room through perforated tiles into the cold aisle in front of the computers. Air flows through the computers exiting at the back into the hot aisle from where the air travels back to the CRAC units for reconditioning. Figure 6.2 describes the hot-aisle cold-aisle concept used in modern data centers. The airflow patterns associated with a typical computer room air handler have a much higher rate of air change than do typical comfort cooling air conditioners. This means that the air is filtered much more often than would be the case in an office environment. Proper filtration can thus accomplish a higher degree of particulate arrestance in a data center.

Particulate filtration is often included as an integral part of an air management system in that it may be an original part of the air-handling equipment, added to an existing HVAC system, or employed as a stand-alone unit. Filtering may take place in the recirculated airstream using, for instance, CRAC units as shown in Figure 6.2, in the makeup air supplied from the outdoor environment, and/or applied directly in some datacom equipment.

ANSI/ASHRAE Standard 52.2-2007 (ASHRAE 2007) is used for rating filters based on their collection efficiency, pressure drop, and particulate-holding capacity. This standard measures arrestance, dust spot efficiency, and dust-holding capacity. Arrestance is a measure of a filter's ability to capture a mass fraction of coarse dust, and dust spot efficiency is the ability to capture particles within a given size range. ANSI/ASHRAE Standard 52.2-2007 also measures particle size efficiency expressed as a minimum efficiency reporting value (MERV) between 1 and 20. Table 6.2 shows the filter rating values from ANSI/ASHRAE Standard 52.2-2007.

For recirculated air, particulate filters with a MERV 8 rating are recommended as a minimum in ANSI/ASHRAE Standard 127-2007 (ASHRAE 2007) and are commonly available for CRAC units. A MERV 11 to 13 filter should be used with air-side economizers or makeup air handlers. It is worth noting that ANSI/ASHRAE Standard 62.1-2013 (ASHRAE 2013) recommends at least a MERV 6 filter upstream of all cooling coils and that air-cleaning devices shall be provided to clean the outdoor air at any location prior to its introduction to occupied spaces where the national standard or guideline for PM_{10} is exceeded. ANSI/ASHRAE Standard 62.1-2013 also requires that particulate filters or air cleaners with a MERV 11 or higher rating shall be provided where the national standard or guideline for $PM_{2.5}$ is exceeded.

Higher-efficiency filtration may be necessary for some data center environments, especially those in areas with elevated levels of $PM_{2.5}$. Any air being introduced into the data center for ventilation or positive pressurization should first pass through a higher efficiency filter. Ideally, the air should be filtered using filters rated

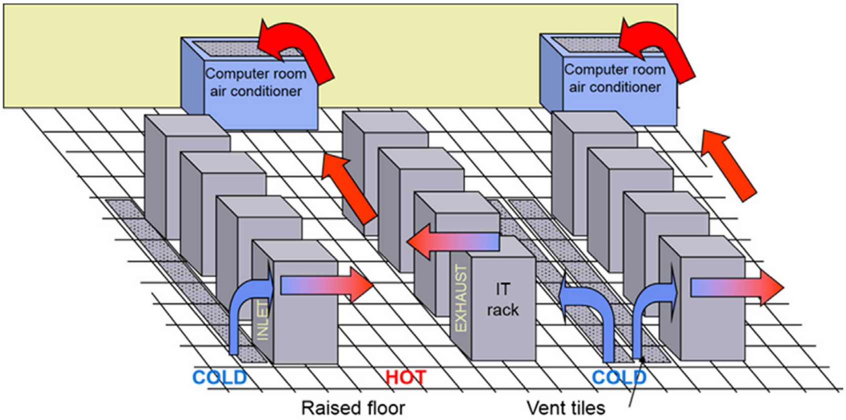

Figure 6.2 Hot-aisle cold-aisle concept showing the airflow pattern in a modern data center.

Table 6.2 Application Guideline

Std. 52.2 Minimum Efficiency Reporting Value (MERV)	Approx. Std. 52.1 Results		Application Guidelines		
	Dust Spot Efficiency	Arrestance	Typical Controlled Contaminant	Typical Applications and Limitations	Typical Air Filter/Cleaner Type
20	n/a	n/a	**≤0.30 µm Particle Size** Virus (unattached) Carbon dust Sea salt All combustion smoke Radon progeny	Cleanrooms Radioactive materials Pharmaceutical manufacturing Carcinogenic materials Orthopedic surgery	HEPA/ULPA Filters ≥99.999% efficiency on 0.10–0.20 µm particles, IEST Type F ≥99.999% efficiency on 0.30 µm particles, IEST Type D ≥99.99% efficiency on 0.30 µm particles, IEST Type C ≥99.97% efficiency on 0.30 µm particles, IEST Type A
19	n/a	n/a			
18	n/a	n/a			
17	n/a	n/a			
16	n/a	n/a	**0.30–1.0 µm Particle Size** All bacteria Most tobacco smoke Droplet nuclei (sneeze) Cooking oil Most smoke Insecticide dust Copier toner Most face powder Most paint pigments	Hospital inpatient care General surgery Smoking lounges Superior commercial buildings	**Bag Filters** Nonsupported (flexible) microfine fiberglass or synthetic media. 300 to 900 mm (12 to 36 in.) deep, 6 to 12 pockets. **Box Filters** Rigid style cartridge filters 150 to 300 mm (6 to 12 in.) deep may use lofted (air laid) or paper (wet laid) media.
15	>95%	n/a			
14	90%–95%	>98%			
13	80%–90%	>98%			

Table 6.2 Application Guideline (Continued)

Std. 52.2 Minimum Efficiency Reporting Value (MERV)	Approx. Std. 52.1 Results		Application Guidelines		
	Dust Spot Efficiency	Arrestance	Typical Controlled Contaminant	Typical Applications and Limitations	Typical Air Filter/Cleaner Type
12	70%–75%	>95%	**1.0–3.0 µm Particle Size** Legionella Humidifier dust Lead dust Milled flour Coal dust Auto emissions Nebulizer drops Welding fumes	Superior residential Better commercial buildings Hospital laboratories	**Bag Filters** Nonsupported (flexible) microfine fiberglass or synthetic media. 300 to 900 mm (12 to 36 in.) deep, 6 to 12 pockets. **Box Filters** Rigid style cartridge filters 150 to 300 mm (6 to 12 in.) deep may use lofted (air laid) or paper (wet laid) media.
11	60%–65%	>95%			
10	50%–55%	>95%			
9	40%–45%	>90%			
8	30%–35%	>90%	**3.0–10.0 µm Particle Size** Mold Spores Hair spray Fabric protector Dusting aids Cement dust Pudding mix Snuff Powdered milk	Commercial buildings Better residential Industrial workplaces Paint booth inlet air	**Pleated Filters** Disposable, extended surface, 25 to 125 mm (1 to 5 in.) thick with cotton-polyester blend media, cardboard frame. **Cartridge Filters** Graded density viscous coated cube or pocket filters, synthetic media **Throwaway** Disposable synthetic media panel filters
7	25%–30%	>90%			
6	<20%	85%–90%			
5	<20%	80%–85%			

Table 6.2 Application Guideline (Continued)

Std. 52.2 Minimum Efficiency Reporting Value (MERV)	Approx. Std. 52.1 Results		Application Guidelines		
	Dust Spot Efficiency	Arrestance	Typical Controlled Contaminant	Typical Applications and Limitations	Typical Air Filter/Cleaner Type
4	<20%	75%–80%	**>10.0 μm Particle Size** Pollen Spanish moss Dust mites Sanding dust Spray paint dust Textile fibers Carpet fibers	Minimum filtration Residential Window air conditioners	**Throwaway** Disposable fiberglass or synthetic panel filters **Washable** Aluminum mesh, latex coated animal hair, or foam rubber panel filters **Electrostatic** Self charging (passive) woven polycarbonate panel filter
3	<20%	70%–75%			
2	<20%	65%–70%			
1	<20%	<65%			

Note: A MERV for other than HEPA/ULPA filters also includes a test airflow rate, but it is not shown here because it has no significance for the purposes of this table.
Source: ANSI/ASHRAE Standard 52.2-2012 (ASHRAE 2012a)

at MERV 13 or high-efficiency particulate air (HEPA) filtration rated at 99.97% efficiency or greater at a particle size of 0.3 microns.

Filtration always impedes the airflow through the air-conditioning system as well as through datacom and infrastructure equipment, therefore, it is important for facility and equipment designs to take the filter impedance into account. Filters should be inspected, replaced, or cleaned at regularly defined intervals to minimize airflow impedance. Some filtration equipment use active alarms based on differential pressure drop to indicate when filters need to be serviced and/or replaced. Manufacturer-defined time intervals may not be accurate because of wide variations in the severity of datacom equipment center environmental conditions.

It is also important that the filters used are properly sized for the air handlers. For instance, gaps around the filter panels can allow air to bypass the filter as it passes through the HVAC system or CRAC unit. Any gaps or openings should be taped, gasketed, or filled using appropriate materials, such as stainless steel panels or custom filter assemblies.

6.2.3 Gaseous Contamination Control

Assuming a building's HVAC system is already equipped with adequate particulate filtration, gaseous filtration can be readily incorporated into the existing air-handling system. Gas phase filters or filtration systems employing various adsorbent and/or chemisorbent media can effectively reduce gaseous contaminants to well below the specified levels. Properly applied, gaseous air cleaning also has the potential for energy savings.

Gas phase filtration can be applied in various locations within and outside a data center. Filters can be added to existing air-handling equipment or supplied in stand-alone pressurization and/or recirculation equipment.

6.2.3.1 Makeup (Outdoor, Fresh) Air Handlers

When outdoor air is being delivered, either directly to the data center or indirectly through a mechanical room, standard side-access systems (Figure 6.3) can be used as powered or nonpowered units designed to control low to moderate levels of gaseous contaminants. This type of system can offer a wide range of prefilters, bulk-fill media modules, and final filters to accommodate specific airflow requirements within the primary outdoor-air-handling system. A secondary unit can be used for recirculation in mechanical or equipment rooms.

Air-side economizers. By definition, an economizer is a mechanical device used to reduce energy consumption. Economizers recycle energy produced within a system or leverage environmental temperature differences to achieve efficiency improvements. The primary concern in this approach to data center cooling is that outdoor air contaminants, both particulate and gas phase, will contaminate the IT equipment.

Research performed at Lawrence Berkley National Laboratory (Shehabi et al. 2007) concluded that the primary concern in a data center with an air-side economizer is the ingress of particulate matter in the form of fine particulates (diameter <2.5 μm) that could cause physical bridging and electrical short circuiting of closely spaced features on PCBs. The study also concluded that "filtration systems in most data centers do just fine in keeping contaminants out" (Shehabi et al. 2007). The Lawrence Berkeley study was, however, limited to particulate filtration, it did not address the issue of gaseous contamination resulting from air-side economizers.

Air-side economizers typically include filters with a minimum ASHRAE-rated particulate removal efficiency of MERV 9 (ASHRAE 2007) to reduce the amount of particulate matter or contaminants that are brought into the data center space. However, in areas with high ambient particulate levels MERV 11-13 (60% to 90%) filters may be required. No references have been found describing the use of gas phase air filter in economizers, even with the advent of RoHS and other lead-free regulations. Adsorbent-loaded nonwoven filters and/or extruded carbon composite

Figure 6.3 Example of chemical filtration system for cleaning outdoor air.

filters can be easily applied in air-side economizer systems to address the gaseous contamination concern.

6.2.3.2 Recirculating Air-Cleaning System

These are typically in-room, self-contained units used to provide additional clean recirculation air to areas with low to moderate levels of gaseous contaminant. Figure 6.4 shows a schematic of a typical recirculating air-cleaning unit. The figure represents a downflow unit that contains (from top to bottom) a MERV 6 to 8 (30% to 40%) particulate prefilter, first stage of bulk-fill chemical filter modules, a blower section, second stage of bulk-fill chemical filter modules, and a MERV 13 to 15 (90% to95%) final particulate filter. These units are used to provide additional filtration of room air in order to maintain very low contamination levels.

6.2.3.3 Positive Pressurization Unit

A positive pressurization unit (PPU) cleans and blows outdoor air into a data center, thus, supplying and pressurizing a data center with clean air. It is a self-contained air filtration system designed to filter low to moderate concentrations of outside air contaminants. The PPU is similar to the recirculation air-cleaning units in that it contains the MERV 6 to 8 (30% to 40%) prefilter, two banks of bulk-fill media modules, a MERV 13 to 15 (90% to 95%) final filter and a blower section. A

Figure 6.4 Self-contained recirculating air filtration system with (from top to bottom) particulate prefilter, chemical filter, motor blower section, chemical filter, and final filter.

PPU may also be equipped with an adjustable damper to vary the ratio of outdoor air it brings in to the air it recirculates in a data center.

6.2.3.4 CRAC Units

CRAC units come equipped with particulate filters. The space allocated to the particulate filters can be retrofitted to use a combination of particulate and gas phase filters. Adsorbent-loaded nonwoven fiber medium can be used for gas phase filtration. These combination filters can maintain the same level of particulate filtration while adding the chemical filtration capability required for the control of low levels of gaseous contamination. The pressure drops of these combination filters are somewhat higher than those of the particulate filters they replace, but still well below the maximum terminal pressure drop tolerated by the CRAC units. Most CRAC units can accommodate standard filter sizes of 50 to 100 mm (2 to 4 in.) in depth (Figure 6.5). If there is adequate head room above the CRAC units, the filter area can be substantially increased by adding a five-sided box structure with combination filters on each side.

Filters with extruded carbon composite (ECC) media may also be used in CRAC units to provide control of low to moderate levels of gaseous contamination.

Figure 6.5 Combination particulate and chemical filter in CRAC unit with filter raised to show details.

Standard 50 and 100 mm (2 and 4 in.) filters are available. Particulate filters should be used in front (upstream) of the ECC filters.

6.2.3.5 Underfloor Air Filtration

Another innovation being considered for the application of gas phase air filtration is the use of ECC filters under the perforated panels on the cold aisles in raised-floor systems. The filter is placed in a customized tray under the perforated panel and fits the dimensions of the existing access floor grid. Gasketing around the filter assembly assures that 100% of the air being delivered into the data center passes through the ECC filter for total gaseous contaminant control. Sealing the subfloor plenum will also help to maximize the amount of air going through the underfloor ECC filters and ultimately the amount of clean air being delivered to data center.

6.2.4 Monitoring for Filtration Effectiveness and Filter Life

Once enhanced air cleaning has been specified and installed, one must determine the effectiveness of the particulate and gas-phase filters in order to ensure their full, most cost-effective use, and at the same time not comprise the data center environment.

6.2.4.1 Particulate Filter Monitoring

Filtration effectiveness can be measured using real-time particle counters in the data center. Excess particle counts or concentrations can indicate filter bypass or failure, internal sources of particle generation (e.g., CRAC belt dust, metal whiskers, etc.), and/or, for instance, if someone left a door open during maintenance or equipment staging.

It is important to know the concentration of particles in a room, it is also useful to know how the contamination is varying over time. Particle counters can provide detailed trend analysis by monitoring gradual or sudden changes in the environment's particle contamination levels.

Particulate filters have specified initial and final pressure drops at rated airflows. Differential pressure gages can be used to observe filter life and set alarm limits. Timely replacement of prefilters, intermediate, and final filters not only protects the IT equipment but also maintains cost-effective, optimum performance of the air-handling equipment.

6.2.4.2 Chemical Filter Monitoring

The primary role of a gas phase filtration system in a data center is to prevent corrosion from occurring on sensitive IT equipment. The best way to measure the effectiveness of gas phase filters is by using passive corrosion classification coupons (CCCs) and/or real-time atmospheric corrosion monitors (ACMs) that monitor the copper and silver corrosion rates (England et al. 1999, Muller 2010).

CCCs can be placed upstream and downstream of the gas phase air filters to gage the systems in reducing total corrosion, individual corrosion species, and in determining when filter replacement is necessary. They can be placed throughout the data center to provide ongoing verification of environmental specifications. ACMs can be placed in the controlled environment and on or in server cabinets to provide a real-time data on corrosion rates and the effectiveness of various gaseous contaminant control strategies—whether they involve the use of gas phase air filtration or not. However, the only air of concern from the IT equipment point of view is the air that enters the equipment. Therefore, from the IT equipment manufacturers' and the IT equipment warranty point of view, the most important location of the CCCs and the ACMs is in front of the IT equipment racks at 1/4 and 3/4 height of the floor, in accordance with the 2011 ASHRAE white paper on particulate and gaseous contamination guidelines for data centers (ASHRAE 2011a).

7

Air-Side Economizers

Air-side economizers are typically used in cold and temperate periods of the year to save energy in datacom equipment center facilities by using outside air to cool the datacom equipment. An air-side economizer typically includes an air-moving device to force large volumes of air into the datacom equipment center, filters to reduce the entry of contaminants, and one or more sensors to regulate the flow of air into the datacom equipment center. The air-side economizer allows the entry of outdoor air when the temperature, humidity, and contamination levels of the outdoor air are below a predetermined level. Integrating economizers for fresh-air cooling in datacom equipment centers is the subject of several other Datacom Series books, including *Best Practices for Datacom Facility Energy Efficiency*, Second Edition (ASHRAE 2009d), which outlines four concerns regarding use of air-side economizers: increased particulate matter, increased gaseous contamination, loss of humidity control, and limited temperature control. This chapter focuses on the gaseous and particulate contamination and humidity concerns of operating air-side economizers.

7.1 IMPLEMENTING AIR-SIDE ECONOMIZERS

A datacom equipment center in most climates can significantly benefit from an air-side economizer. Datacom equipment center cooling needs can often be served using outdoor air during cooler weather, particularly at night when the outdoor air temperatures may be even cooler. An air-side economizer can result in significant cost savings, depending on the size of the economizer load and the hours of operation. The main concern often expressed for not considering an air-side economizer is that large amounts of particulate and gaseous contaminants will enter and degrade the reliability of the datacom equipment. The second concern datacom operators have is over allowing a wider temperature and humidity range needed to take full advantage of air-side economization. There is some validity for these concerns, given that documented failures have occurred in high-humidity and high-temperature environments.

7.1.1 Particulate and Gaseous Contamination Challenge

The detrimental effects of contamination have already been documented in earlier chapters. Air-side economizers can be equipped with particulate and gas phase filters to filter out the contaminants from the incoming air. The contaminant easiest to filter out during an economizer cycle is the coarse dust, defined as having particles with diameter >2.5 μm. Also, coarser dust is less corrosive to metals because it is mostly the result of the erosion of minerals that are low in ionic content. The challenge is to filter out fine dust particles (diameter <2.5 μm) and gaseous contamination, both of which may be corrosive to metals.

The impact of filtering out fine dust particles on the performance and the added energy consumption of air-side economizers fitted with particulate filters of MERV ratings 7, 11, and 14 has been studied by Lawrence Berkeley National Laboratory (Ganguly et al. 2009) in a data center located in Sunnyvale, CA, near a major interstate highway. The baseline for comparison was a conventional air-handling-based cooling system. A key finding was that the indoor proportion of outdoor particles (IPOP) decreased as the MERV rating of the filters used in the economizer-based system was increased from 7 to 11 to 14. This trend held true for all the particle types monitored: fine dust particles and fine carbon black particles. It also held true for the ionic content (sulfates and nitrates) of the particles monitored. The particle contamination in the data center in Sunnyvale was found to be less when the air-side economizer was operated with MERV 14 filters compared to when the conventional air-handling-based cooling system was operated. The HVAC energy savings with the use of MERV 7 filter in air-side economizers was 56% compared to the baseline conventional air-handling system. The corresponding HVAC energy savings with the use of MERV 14 was 38%. This reduction in energy saving is a small price to pay considering that a data center with an air-side economizer using a MERV 14 filter will have less particulate concentration than found in a typical data center without air-side economizer.

The performance and economy of air-side economizers with gas phase filtration has not been as well studied. With a few localized and regional exceptions, the outdoor air in North America and Western Europe is benign with respect to electronic equipment corrosion. In these regions, the use of gas phase filtration of air delivered into the data center by air-side economizers is generally not required, but particulate filtration should be required. The outdoor air quality in most of the major cities in South Asia and China is, however, very poor. The air is heavily polluted with particulate and gaseous contaminants that originate from the same sources: the burning of low-grade coal in power generation plants and the high levels of motor vehicle exhaust in and around major population centers. In these polluted geographies, the economics of air-side economizers using gas phase filtration may not be attractive. The higher volumes and concentrations of gaseous contamination will require careful consideration of the type of chemical filters such that they do not deplete too rapidly and therefore require frequent change of the filter media, making air-side economizers economically inviable.

However, there is a possibility that air-side economizers may be economically viable even in polluted Asian geographies. The possibility rests on the hypothesis that creep corrosion, the most troubling and least understood failure mechanism, may require two necessary conditions to occur: the presence of both fine particles uniformly coating the PCBs and high levels of gaseous contamination (Fu et al. 2014). In other words, gaseous contamination by itself may not be sufficient to cause creep corrosion on PCBs. Fine dust is of particular concern because the water-soluble ions represent a significantly greater fraction of its mass (Sinclair 1985). The water-soluble salts in fine dust are mainly ammonium sulfate, ammonium hydrogen sulfate, and ammonium nitrate (Zhang et al. 2004). Of these, ammonium hydrogen sulfate has the lowest deliquescent relative humidity of 40% (Frankenthal et al. 1993). Depending on the composition, fine dust can have an effective deliquescent relative humidity of 50% to 65% (Litvak et al. 2000). In contrast, the effective deliquescent relative humidity of most clean metal surfaces is in the range 70% to 80% (Frankenthal et al. 1993). Fine dust on surfaces can have three detrimental effects: (1) if the relative humidity in the room is above the deliquescent relative humidity of the dust, the dust will get wet and support corrosion, (2) the increased surface area due to the fine dust will provide additional area on which gases can be adsorbed, thus increasing the rate of corrosion of the underlying metal, (3) dust particles can increase the rate of corrosion through differential aeration. It is speculated here that the influence of fine dust may be so overwhelming that it may be playing a dominant role in the creep corrosion on PCBs. If this hypothesis is true, it may be sufficient to filter out the fine particles using MERV 14 or higher rated filters and not require any gas phase filtration to avoid creep corrosion. Other forms of corrosion may still occur, such as of silver-terminated surface-mount resistors, but this corrosion may be eliminated by making the product robust by design.

7.1.2 Humidity and Air-Side Economizers

Some air-side economizer implementations have the capability of adding humidity to the incoming airstream. This is typically done either to offset low humidity levels of the incoming air, or as a means of evaporative cooling of the incoming air during periods of warm weather. Adding water to the incoming air, if not done correctly, can release mineral salts into the air and then into the datacom equipment. These salts become conductive and corrosive if the room's relative humidity is above their deliquescent relative humidity. The introduction of the salts is exacerbated when water vapor is introduced from large building humidification systems or local ultrasonic systems, unless deionized water is used. Both these systems introduce water directly into the air where small droplets evaporate leaving behind tiny particles of suspended salt. Evaporative systems such as a steam generators or infrared lamps over pans of water do not release contamination into the air unless over time salt cakes up on the sides walls of the water troughs and erodes into the air. Regardless of which humidification system is used, water quality and purity are important in reducing scale buildup within the humidifier equipment and eliminating airstream mineral dusting.

7.2 FACTORS TO CONSIDER FOR SUCCESSFUL DEPLOYMENT OF AIR-SIDE ECONOMIZERS

Despite contamination risks, air-side economizers still represent a significant opportunity to save energy when the external ambient conditions are suitable for eliminating the need for the mechanical refrigeration process. Air-side economizers can certainly be utilized in a datacom environment and should be given full consideration during the design process, but care must be taken with regard to contaminants when implementing these systems. There are several things to consider in order to deploy air-side economizers successfully:

- **Location:** Understand the surrounding environment and identify potential threats. For example, is the datacom facility located near a hazardous industry plant (e.g., paper mill, a farm, or an airport)?
- **Weather:** Choice of geographic location is an important consideration for maximizing the number of hours available for air-side economization. If there are localized sources of pollutants such as factories and agriculture, wind direction can also be an important factor.
- **Geography:** Some geographies are heavily polluted with fine dust and gaseous contamination from the burning of low-grade coal to generate power. If it is proven that both fine particles and gaseous contamination are required to cause creep corrosion on PCBs, then air-side economizers may be feasible in these geographies if MERV 14 and higher-rated filters are used to filter out the fine particles from entering the datacom equipment center.
- **Nature:** Catastrophic events like forest fires or volcanic eruptions can send contaminants thousands of meters into the air, which can travel over long distances.
- **Filtration:** The selection of filters must include consideration of the amount of airflow and pressure drop across each stage of filtration as well as the type of contamination to be removed. Local air quality data can be obtained for both particulate and chemical contamination levels to aid in the selection of proper filters. Whenever possible, the filters for particulate and chemical contamination should be separate. In cases of physical limitations of size, pressure drop, and space, commercially available combination particulate and chemical filters may be used.
- **Monitoring and controls:** For datacom environments with air-side economizers, it is necessary to incorporate real-time monitoring and controls capable of reacting quickly to unexpected events that could release particulates or corrosive gases. Detection equipment in the marketplace today can provide real-time monitoring and reporting of corrosive, odorous, hazardous, and toxic gases and can gauge the real-time effects of corrosion on electronics. One such product uses patented copper- and silver-plated quartz crystal microbalance (QCM) sensors to measure the mass accumulation of corrosive film on copper and silver. By applying the proper conversion factors, the

> product correlates the mass gain to corrosion thickness, expressed in ångströms. This measurement can then be related to the ANSI/ISA Standard 71.04-1985, *Environmental Conditions for Process Measurements and Control Systems: Airborne Contaminants* (ISA 1985), classes shown in Table 6.1. Airflow or pressure drop monitoring must also be incorporated across the filters to sense the amount of blockage due to particulate matter and alert datacom staff so the filter media can be replaced.

It is essential that the proper monitoring and controls are in place to react to contaminating events outside the data center that may have the potential of seriously contaminating the datacom equipment. With proper monitoring, filtering, and controls systems in place, even these intermittent contaminating events can be properly handled.

8

Summary

The increase in the rate of IT and datacom equipment corrosion-related failures starting in the mid-2000s has been attributed to (1) the proliferation of data centers in the geographies of Asia that are high in sulfur-bearing gases, (2) the reduction of circuit board feature sizes, (3) the miniaturization of components, and (4) the requirement that IT and datacom equipment comply with the RoHS directives of the European Union. These increased failure rates led to the publication of ASHRAE's *Particulate and Gaseous Contamination in Datacom Environments* (2009c) book and to the publication of ASHRAE's *Particulate and Gaseous Contamination Guidelines for Data Centers* (2009a) white paper that recommended that in addition to temperature and humidity control, dust and gaseous contamination should also be monitored and controlled. These additional environmental measures, important for data centers located near industries and/or other sources that pollute the environment, are necessary to reduce the two most common recent failure modes of copper creep corrosion on PCBs and the corrosion of silver metallization in miniature surface-mounted components. It should be noted that the reduction of PCB feature sizes and the miniaturization of components, necessary to improve hardware performance, also makes the hardware more prone to attack by the corrosive particles and gases in the data center environment. Manufacturers are in a constant struggle to maintain the reliability of their hardware with ever-shrinking feature sizes, without taking the added costly measure of hardening all their IT equipment, most of which is not installed in corrosive environments where it can be exposed to a higher risk of failure.

Another factor adding to the greater necessity of monitoring, preventing, and controlling particulate and gaseous contaminations in data centers is that the ASHRAE TC 9.9 subcommittee has expanded the recommended and allowable temperature and humidity ranges to provide greater flexibility in data center facility operations, particularly with the goal of reducing energy consumption (ASHRAE 2012c). Today, the recommended limits are 18°C to 27°C (64.4°F to 80.6°F) dry-bulb temperature, relative humidity less than 60% with the lower and upper dew-point temperatures of 5.5°C and 15°C (41.9°F and 59°F). The newly added allowable classes A3 and A4 extend the dry-bulb temperature to 40°C and 45°C (104°F and 113°F), the relative humidity to 85% and 90%, respectively, with the upper end dew point at 24°C (75.2°F) for both these allowable classes. The downside of expanding the temperature-humidity envelope is the greater corrosion-related reliability risk from the gaseous and particulate contamination in data centers.

With the increasing pressure to reduce energy consumption leading to the increasing use of air-side economizers, data centers located in polluted geographies will struggle to maintain hardware reliability without the application of enhanced air cleaning. This means increasing particulate filter efficiencies to at least an ASHRAE MERV 13 rating and the addition of gas phase air filtration designed to control specific contaminants of concern.

It is incumbent on data center managers to do their part in maintaining hardware reliability by monitoring, preventing, and controlling the particulate and gaseous contamination in their data centers. A proper contamination control strategy designed to meet ASHRAE guidelines and standards must consist of at least three fundamental steps:

1. Assessment based on measuring and monitoring
2. Contamination control and removal based on industry best practices as well as proper selection and application of particulate and gas phase filtration
3. Ongoing monitoring to track changes in contamination levels to ensure effectiveness of selected contamination control strategies

Data centers must be kept clean to ISO Standard 14644-1 Class 8 (ISO 1999). This level of cleanliness can generally be achieved by an appropriate filtration scheme as outlined here:

1. The room air should be continuously filtered with MERV 8 filters as recommended by ANSI/ASHRAE Standard 127-2007, *Method of Testing for Rating Computer and Data Processing Room Unitary Air Conditioners* (ASHRAE 2007).
2. Air entering a data center should be filtered with MERV 11 to MERV 13 filters as recommended in Chapter 6 (ASHRAE 2014).

Sources of dust inside data centers should be reduced. Every effort should be made to filter out dust that has deliquescent relative humidity greater than the maximum allowable relative humidity in the data center. The gaseous contamination should be within the ANSI/ISA Standard 71.04-2013 severity level G1 that meets (ISA 2013):

1. a copper reactivity rate of less than 300 Å/month
2. a silver reactivity rate of less than 200 Å/month

For data centers with higher gaseous contamination levels, gas phase filtration of the inlet air and the air in the data center is highly recommended. The adherence to the requirements outlined herein is important to maintain high reliability of the datacom and IT equipment and avoid the cost of hardware replacement not covered under warranty.

Appendix A

Coulometric Reduction Analysis of Corrosion Classification Coupons

Coulometric reduction analysis involves exposing clean copper and silver foils to the air in the data center being monitored. Any size metal foils, called corrosion classification coupons, may be employed. A convenient size for foils is 25 × 50 mm (1 × 2 in.). They can be stuck inside a 50 × 50 mm flat plastic box, as shown in Figure A.1. The metal foils are degreased, wet abraded with 600 grit paper, using deionized water, followed by rinsing with deionized water and then isopropyl alcohol and dried before sticking to the inner surfaces of plastic boxes. The plastic boxes are closed and stored in sealed plastic bags with desiccant. In the data center to be monitored, the boxes are opened and stuck to the air inlet faces of the computers racks suspected of being exposed to contaminated air. Figure A.2 shows two boxes on the inlet face of a computer rack. The 1/4 and 3/4 heights are the heights of exposure recommended by the 2011 ASHRAE white paper on data center contamination (ASHRAE 2011a). After the recommended exposure duration of one month, the plastic boxes are removed from the computer, closed, sealed in plastic bags with desiccant, and returned to the laboratory for coulometric reduction thickness measurement of the corrosion products on the corrosion classification coupons.

The corrosion products on metal surfaces can be electrochemically reduced to metal by applying cathodic current. The metal coupon under test is immersed in a deaerated 0.1 mol KCl electrolyte and its potential is measured as a function of time while it is subjected to a constant cathodic current density typically equal to 0.05 mA/cm^2. The potential versus time plot has plateaus, one for each type of corrosion product that is reduced. From the coulombs associated with each corrosion product's plateau, the thickness of the corrosion product can be calculated. The following paragraphs describe the coulometric reduction method. Additional details can be found in a paper by Krumbein (1989).

The silver and copper foils, returned to the laboratory after one month of exposure in a datacom environment, are analyzed using coulometric reduction. The details of the analysis vary from laboratory to laboratory. One method that uses the standard glassware of ASTM Standard G5-94 is described here in detail (ASTM 2011). Figure A.3 shows the glassware and the polytetrafluorethylene specimen holder. The foils exposed in the field for one month are sheared into 16 mm (5/8 in.) diameter disks. Each 25 × 50 mm (1 × 2 in.) foil results in three disks as shown in Figure A.4. The sample holder is designed such that only the corroded face of the foil is exposed to the 0.1 mol KCl

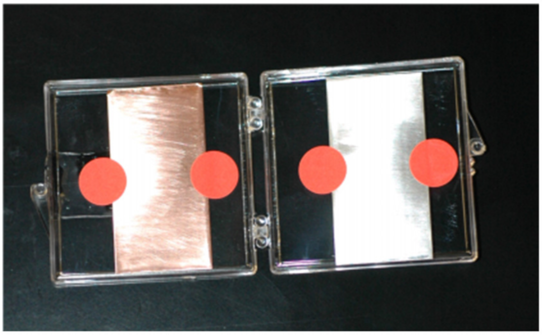

Figure A.1 A 50 x 50 mm (2 x 2 in.) plastic box with a copper and a silver foil attached with sticky dots. The box is show in the open state to allow the exposure of the metal foils to the environment.

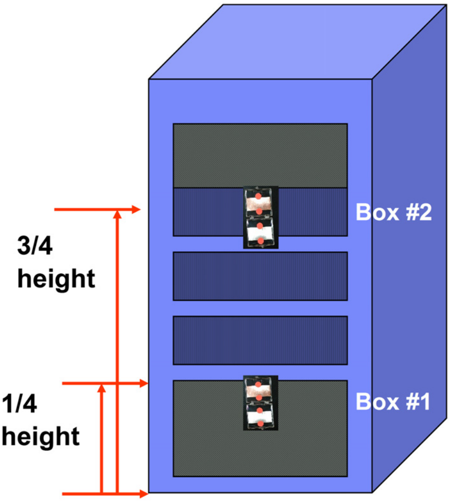

Figure A.2 Two sets (boxes) of corrosion classification coupons exposed to the air entering the front face of a computer rack at 1/4 and 3/4 height off the floor.

(a) (b)

Figure A.3 Glassware of ASTM Standard G5-94 for coulometric reduction (a), metal coupon, mounted in a polytetrafluorethylene enclosure (b) (ASTM 2011).

Figure A.4 Coupons, 16 mm (5/8 in.) diameter, are punched out of the 25 x 50 mm (1 × 2 in.) foil exposed for one month in the field. Notice that three coupons can be punched out to make three coulometric reduction runs. Generally, only one or two runs are necessary. The remaining metal foil, as shown above, can be achieved.

electrolyte. No other metal part is exposed to the electrolyte. The diameter of the exposed foil face is ~11 mm. A potentiostat applies 0.05 mA constant cathodic current to the ~11 mm diameter metal foil while its potential is measured, typically, with a calomel reference electrode. The counter electrode used to apply the cathodic current is made of an electrochemiocally stable material such as graphite or platinum.

When the constant cathodic current is passed between the graphite or platinum counter electrode and the metal foil through the electrolyte, the potential of the foil with respect to the calomel reference electrode will rise with time, with a few plateaus. The output of a coulometric reduction run is a potential versus time graph that shows plateaus in the potential corresponding to each chemical species being reduced. For silver, there can generally be only two plateaus: one for silver chloride reduction and the other for silver sulfide reduction. A plot showing only silver sulfide reduction is shown if Figure A.5. Copper coulometric reduction potential versus time plots can have three plateaus corresponding to the reduction of cuprous oxide, cupric oxide, and cupric sulfide as shown in Figure A.6. Once all of the corrosion products on the surface of the coupon are reduced, water itself is reduced by the coupon acting as a cathode. A long flat potential results.

Table A1 gives the potentials at which the plateaus occur for various commonly occurring corrosion products on silver and copper and the factors for calculating the thickness of the known corrosion product films.

The reduction potentials in Table A-1 are with respect to a Ag/AgCl reference electrode in 0.1 mol KCl solution. The potentials measured using a saturated calomel reference electrode would only differ by 0.04 V. Reduction potentials are somewhat dependent on current density.

Often plateaus arise that are not in the above table. One such example of an unknown plateau for silver corrosion product at about 1.2 V with respect to standard calomel electrode. Surface analysis has shown that this plateau does not correspond

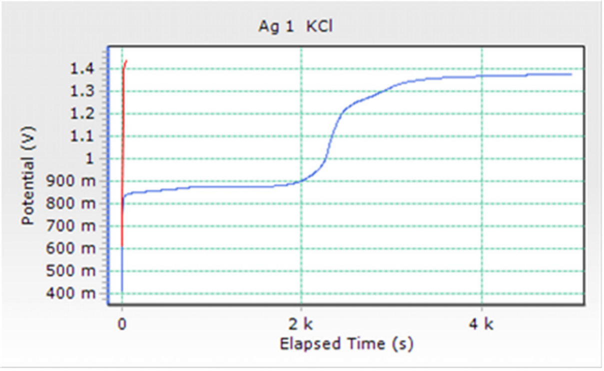

Figure A.5 Silver sulfide plateau on a silver coupon.

to any silver compound reduction. Unidentified plateaus should not be used in calculating the corrosion product thickness.

The analysis of the potential-time plots begins by calculating the time period of the plateaus. One can estimate the plateau times by visual inspection, or for more accuracy, one can plot the first derivative of the potential-time graph. The peaks in the first derivative plot more accurately indicate the start and end of a plateau. The thickness of a known corrosion product whose plateau time period is known at a known constant current density can be calculated as follows:

$$T = jtK$$

where T is the thickness in ångströms, j is the current density in mA/cm^2, and K is given by

$$K = \frac{10^5 M}{NFd}$$

where M is the molecular weight, d is the density in g/mL of the known corrosion product, F is the Faraday's constant equal to 96,485 coulombs/equivalents and N is the number of electrons exchanged in the reduction of the one molecule of the corrosion product. As an example, let us calculate the K factor for Ag_2S, the most important corrosion product for data center air quality monitoring:

$$K = \frac{10^5 M}{NFd} = \frac{10^5(247.8)}{(2)(96{,}500)(7.32)} = 17.5$$

Simply summing the thickness of all the corrosion products provides a total corrosion product thickness on the coupons in ångströms.

Table A.1

Chemistry	Density, g/mL	Molecular Weight	Reduction Potential	*K* Factor
AgCl	5.56	143.3	0	26.7
Ag_2S	7.32	247.8	0.82	17.5
Cu_2O	6.0	143.1	0.55–0.75	12.4
CuO	6.4	79.54	0.7–0.9	6.43
Cu_2S	5.6	159.1	1.0–1.15	14.7

Source: "Monitoring Environmental Tests by Coulometric Reduction of Metallic Control Coupons," *Journal of Testing and Evaluation* (Krumbein 1989).

Figure A.6 An alternate design of corrosion classification coupons. Copper and silver metal strips are attached by polytetrafluorethylene fasteners off a plastic plate. The metal strips are unfastened and coulometric reduction analyzed to get the corrosion product thickness.

The coulometric reduction technique does have its limitations. Very thick (>1 µm) films cannot be analyzed due to poor adhesion of the layers to the coupon metal. Also, the resolution of the film components may be ambiguous if the reduction occurs at close potentials. The final thickness of the film on the coupons can be correlated to the ISA Standard 71.04 to determine the level of environmental corrosivity level (ISA 2013).

Appendix B

Relationship of Corrosion Rate Units for Copper and Silver

Papers on atmospheric corrosion of metals often report corrosion rates in terms of rate of weight gain in μg/cm²·h. ANSI/ISA Standard 71.04 reports corrosion rates in terms of the rate of increase of corrosion product thickness in Å/month (ISA 2013).

The relationship of the two rates for silver corrosion is derived below. In this calculation, it is assumed that Ag_2S is the only corrosion product and that the density of Ag_2S is 7.23 g/cm³.

Silver specimen weight gain of 1 μg

$$\equiv \frac{2 \times 107.9 + 32}{32}\ \mu\text{g of } Ag_2S$$

$$\equiv 7.74 \times 10^{-6}\ \text{g of } Ag_2S$$

$$\equiv \frac{7.74 \times 10^{-6}}{7.23}\ \text{cm}^3\ \text{of } Ag_2S$$

$$\equiv 1.07 \times 10^{-6}\ \text{cm}^3\ \text{of } Ag_2S$$

1 μg/cm²·h

$$\equiv 1.07 \times 10^{-6}\ \text{cm/h}$$

$$\equiv 1.07 \times 10^{-6} \times 10^{8}\ \text{Å/h}$$

$$\equiv 107 \times 24 \times 30\ \text{Å/30 d}$$

$$\equiv 7.7 \times 10^{4}\ \text{Å/30 d}$$

If we assume that the silver corrosion product is mostly Ag_2S, then a 300 Å/month rate of corrosion product growth is equivalent to 0.0039 $\mu g/cm^2 \cdot h$ rate of weight gain.

The relationship of the two rates for copper corrosion is derived below. In this calculation, it is assumed that Cu_2S is the only corrosion product and that the density of Cu_2S is 5.6 g/cm^3.

Copper specimen weight gain of 1 μg

$$\equiv \frac{2 \times 63.55 + 32}{32} \ \mu g \text{ of } Cu_2S$$

$$\equiv 5 \times 10^{-6} \text{ g of } Cu_2S$$

$$\equiv \frac{5 \times 10^{-6}}{5.6} \text{ cm}^3 \text{ of } Cu_2S$$

$$\equiv 0.9 \times 10^{-6} \text{ cm}^3 \text{ of } Cu_2S$$

1 $\mu g/cm^2 \cdot h$

$$\equiv 0.9 \times 10^{-6} \text{ cm/h}$$

$$\equiv 0.9 \times 10^{-6} \times 10^{8} \ \text{Å/h}$$

$$\equiv 90 \times 24 \times 30 \ \text{Å/30 d}$$

$$\equiv 6.4 \times 10^{4} \ \text{Å/30 d}$$

The relationship between the two rates for copper corrosion is derived below. In this calculation, it is assumed that Cu_2O is the only corrosion product and that the density of Cu_2O is 6 g/cm^3.

Copper specimen weight gain of 1 μg

$$\equiv \frac{2 \times 63.55 + 16}{16} \ \mu g \text{ of } Cu_2O$$

$$\equiv 8.94 \times 10^{-6} \text{ g of } Cu_2O$$

$$\equiv \frac{8.94 \times 10^{-6}}{6} \text{ cm}^3 \text{ of } Cu_2O$$

$$\equiv 1.5 \times 10^{-6} \text{ cm}^3 \text{ of } Cu_2O$$

1 $\mu g/cm^2 \cdot h$

$$\equiv 1.5 \times 10^{-6} \text{ cm/h}$$

$$\equiv 1.5 \times 10^{-6} \times 10^{8} \text{ Å/h}$$

$$\equiv 1.5 \times 10^{2} \times 24 \times 30 \text{ Å/30 d}$$

$$\equiv 10.8 \times 10^{4} \text{ Å/30 d}$$

If we assume that copper corrodes to Cu_2S and Cu_2O in equal proportions, we can estimate the relation of the two rates of copper corrosion as

$$1 \ \mu g/cm^2 \cdot h \equiv 8.6 \times 10^{4} \text{ Å/30 d}$$

If we assume that the copper corrosion product is 50% Cu_2S and 50% Cu_2O, then 300 Å/month rate of corrosion product growth is equivalent to 0.004 $\mu g/cm^2 \cdot h$ rate of weight gain. Then, 300 Å/month rate of corrosion product growth is equivalent to 0.0035 $\mu g/cm^2 \cdot h$ rate of weight gain.

The relationship between the two rates for copper corrosion is derived below. In this calculation, it is assumed that Cu_2O is the only corrosion product and that the density of Cu_2O is 6 g/cm^3.

Copper specimen weight gain of 1 µg

$$\equiv \frac{2 \times 63.55 + 16}{16} \ \mu g \text{ of } Cu_2O$$

$$\equiv 8.94 \times 10^{-6} \text{ g of } Cu_2O$$

$$\equiv \frac{8.94 \times 10^{-6}}{6} \text{ cm}^3 \text{ of } Cu_2O$$

$$\equiv 1.5 \times 10^{-6} \text{ cm}^3 \text{ of } Cu_2O$$

1 $\mu g/cm^2 \cdot h$

$$\equiv 1.5 \times 10^{-6} \text{ cm/h}$$

$$\equiv 1.5 \times 10^{-6} \times 10^{8} \text{ Å/h}$$

$$\equiv 1.5 \times 10^{2} \times 24 \times 30 \text{ Å/30 d}$$

$$\equiv 10.8 \times 10^{4} \text{ Å/30 d}$$

If we assume that copper corrodes to Cu_2S and Cu_2O in equal proportions, we can estimate the relation of the two rates of copper corrosion as

$$1\ \mu g/cm^2 \cdot h \equiv 8.6 \times 10^4\ \text{Å}/30\ d$$

If we assume that the copper corrosion product is 50% Cu_2S and 50% Cu_2O, then 300 Å/month rate of corrosion product growth is equivalent to 0.004 $\mu g/cm^2 \cdot h$ rate of weight gain. Then, 300 Å/month rate of corrosion product growth is equivalent to 0.0035 $\mu g/cm^2 \cdot h$ rate of weight gain.

Appendix C

Field Contamination Occurrences

The major repercussions of contamination of datacom equipment center and computer equipment operation are often intermittent. Issues do not arise from minor irregularities that can influence the system's steady-state condition, but occur when there is a severe change in one or more of the facility's systems.

For example, if floor panels are lifted in a contaminated datacom equipment center without the smoke detection system being deactivated first, single or multiple alarms may occur. Normally, raised-access floor datacom equipment center detection systems are cross-zoned using both photoelectric and ionization-type detectors. The cross-zoning configuration provides protection against false discharges of the suppression system by requiring one of each type of detector to be in the alarm state prior to the initiation of a suppressant discharge. However, severe contamination conditions and service provider activities may make these safeguards ineffective. Without immediate action by on-site facilities personnel, alarm activation could cause a release of the fire suppression agent, a shutdown of the air handlers, an activation of the computer hardware disconnecting means, or a combination of these events. Even if the datacom equipment is not shut down, some datacom hardware will not operate very long without proper cooling if the air-handling systems are unavailable.

The following are some real example of how contaminants have impacted the operation of the datacom equipment center.

- **Agricultural field in proximity to a datacom center.** The datacom equipment center was impacted by a nearby agriculture field that was plowed twice each year, in the spring and fall during the time the datacom equipment center room was cooled using an air-side economizer. Numerous times, dust clouds generated from the field plowing went unnoticed and blocked the air intake filters of the economizer system. The economizer's compromised filter system caused an increase in the datacom equipment center facility and datacom equipment temperatures. In addition, the fine particles of the dust triggered the smoke detectors. If datacom facility personnel had not been on-site to react immediately, such as is the case during nights and weekends, the datacom center may have experienced an unscheduled outage. Eventually, personnel realized that the economizer and facility had to be serviced and cleaned twice a year, resulting in an additional operating expense.

- **Datacom center affected by low relative humidity because of regional wind patterns (Santa Ana, CA winds).** This event occurred in a datacom equipment center that used an air-side economizer as much as possible and periodically experienced intermittent hardware failures. The root cause of these intermittent failures resulted from external wind pattern shifts. When strong, extremely dry, offshore winds occurred, the relative humidity in the datacom equipment center dropped to as low as 10%. When this occurred at night, the air temperatures were low enough to maintain the use of air-side economizers, but the humidification system could not keep up with the introduction of the very dry air. With no one on site to react to these dry conditions, the relative humidity plummeted and the hardware failed.
- **A pharmaceutical lab with a massive engine generator plant to supply emergency power to the facility.** At this facility, the generators were started and tested each week during normal business hours. During start-up and testing, a huge plume of smoke was released into the air, and the local winds carried the smoke to surrounding buildings. The fumes entered into the buildings and datacom center, activating multiple smoke alarms and forcing the evacuation of personnel. Fortunately, the maintenance staff was available during the day and aborted the dumping of the inert gas fire suppression system, thereby preventing a datacom outage. However, if this event had occurred at night or on a weekend, the datacom center may have experienced an unscheduled outage, because no one would have been immediately available to react to the alarms.
- **Air intake for the datacom center is adjacent to a parking lot serving a neighboring company's loading dock (another diesel smoke incident).** In this example, the datacom equipment center's air-side economizer air intake was located adjacent to a neighboring company's parking lot and loading dock. During normal operations, truck drivers would park in the lot and idle, waiting their turns at the loading dock. One night, multiple alarms were set off because of the amount of diesel exhaust fumes that entered the datacom center.

Glossary of Terms

advection: the transfer of heat by the horizontal movement of air.

aethalometer: an instrument used to measure real-time particulate matter concentration.

anthropogenically: creation of particulate matter from humans.

arrestance: the amount of synthetic dust a filter is able to capture.

coulometric reduction: a method used to measure the copper corrosion rate on metal surfaces.

CRAC: computer room air conditioner, generally refers to computer room cooling units that use dedicated compressors and refrigerant cooling coils rather than chilled-water coils.

CRAH: computer room air handler, generally refers to computer room cooling units that utilize chilled-water coils for cooling rather than dedicated compressors.

data center: any datacom environment dedicated to housing and operating equipment used in the transfer, storage, and processing of electrical signals for communication or computation.

NOTE: A data center is a datacom environment, but a datacom environment is not necessarily a data center. The operative differentiator is *dedicated environment*.

datacom: a term that is used as an abbreviation for the data and communications industry.

datacom environment: any area used to house or mount equipment used in the transfer, storage, and processing of electrical signals for communication or computation.

datacom equipment center: a building or portion of a building where the primary function is to house a computer room and its support areas. Datacom equipment centers typically contain high-end servers and communication and storage products with mission-critical functions.

datacom technology: any equipment used in the transfer, storage, and processing of electrical signals for communication or computation. Equipment may or may not actively alter the electrical signals (e.g., punchdown block and cabling versus server or network switch).

deliquesce: salts that become a liquid by absorbing moisture from the air.

dew point: the temperature at which water vapor has reached the saturation point (100% relative humidity).

dust spot efficiency: a measure of the ability of the filter to remove atmospheric dust from the test air.

EDX: energy-dispersive x-ray, a spectroscopy technique that is an analytical technique used for the elemental analysis or chemical characterization of a particulate matter sample.

HEPA: high-efficiency particulate air.

HEPA filter: filters designed to remove at least 99.97% or more of all airborne particles 0.3 μm or larger from the air that passes through the filter. There are different levels of cleanliness, and some HEPA filters are designed for even higher removal efficiencies and/or removal of smaller particles.

HVAC: heating, ventilation, and air conditioning, in the datacom equipment center, HVAC systems control the ambient environment (i.e., temperature, humidity, airflow, and air filtering) and must be planned for and operated along with other datacom center equipment, such as computing hardware, cabling, data storage, fire protection, physical security systems, and power.

hygroscopic: substances that can attract, absorb, and retain moisture from the atmosphere.

IEC: International Electrotechnical Commission, a not-for-profit, nongovernmental international standards organization that prepares and publishes international standards for all electrical, electronic, and related technologies—collectively known as *electrotechnology*. IEC standards cover a vast range of technologies from power generation, transmission, and distribution to home appliances and office equipment, semiconductors, fiber optics, batteries, solar energy, nanotechnology, and marine energy, as well as many others. The IEC also manages three global conformity assessment systems that certify whether equipment, systems, or components conform to international standards.

infiltration: flow of outdoor air into a building through cracks and other unintentional openings and through the normal use of exterior doors for entrance and egress, also known as *air leakage into a building*.

ISO: International Organization for Standardization, an international standard-setting body composed of representatives from various national standards organizations. The organization promulgates worldwide proprietary industrial and commercial standards. While ISO defines itself as a nongovernmental organization, its ability to set standards that often become law, either through treaties or national standards, makes it more powerful than most nongovernmental organizations. In practice, ISO acts as a consortium with strong links to governments.

MERV: minimum efficiency reporting value, the MERV rating on an air filter describes its efficiency as a means of reducing the level of 3 to 10 μm particles in air that passes through the filter. Higher MERV means higher filter efficiency. The purpose of the MERV standard is to permit an equal comparison of the filtering efficiency of various air filters.

PM: particulate matter, a generic term used to describe a complex group of air pollutants that vary in size and composition, depending upon the location and time of its source. The particulate matter mixture of fine airborne solid particles and liquid droplets (aerosols) include components of nitrates, sulfates, elemental carbon, organic carbon compounds, acid aerosols, trace metals, and geological material. Some of the aerosols are formed in the atmosphere from gaseous combustion by-products such as volatile organic compounds, oxides of sulfur (SO_X), and nitrogen oxides (NO_X). The size of particulate matter can vary from coarse windblown dust particles to fine particles directly emitted or formed from chemical reactions occurring in the atmosphere.

RH: relative humidity, a ratio of the partial pressure or density of water vapor to the saturation pressure or density, respectively, at the same dry-bulb temperature and barometric pressure of the ambient air. At 100% rh, the dry-bulb, wet-bulb, and dew-point temperatures are equal.

RoHS: restriction of hazardous substances, RoHS regulations are European Union regulations enforceable after July 1, 2006, that set maximum concentration limits on hazardous materials used in electrical and electronic equipment. The substances are lead, mercury, cadmium, hexavalent chromium, polybrominated biphenyls, and polybrominated diphenyl ethers flame retardants. There are some datacom equipment exemptions, depending on the device being manufactured. There are some exceptions, such as lead in solders used in high-reliability applications, for which there is no known substitute. Mercury is permitted in limited quantities in some fluorescent lamps yet unrestricted in other types.

SEM: scanning electron microscope, a sophisticated microscope that uses a high-energy beam. It collects signals, reflected from an object's surface, which indicate material properties such as composition and electrical conductivity.

telecom: abbreviation for telecommunications.

TSP: total suspended particulate, a measured parameter of the solid particles (e.g., wood, process dust, and smoke) found in air emissions. These tiny airborne particles or aerosols that are less than 100 µm are collectively referred to as *total suspended particulate matter*. These particles constantly enter the atmosphere from many sources. For example, they result from motor vehicle use, combustion products from space heating, industrial processes, power generation, soil, bacteria and viruses, fungi, molds and yeast, pollen, salt particles from evaporating sea water, and many others.

VOCs: volatile organic compounds, organic chemical compounds that have high enough vapor pressures under normal conditions to significantly vaporize and enter the atmosphere. A wide range of carbon-based molecules, such as aldehydes, ketones, and other light hydrocarbons, are VOCs.

whiskers: crystalline metallurigical phenomenon whereby iron, tin, and zinc grow tiny hairs that can become airborne under certain conditions and settle in datacom equipment.

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