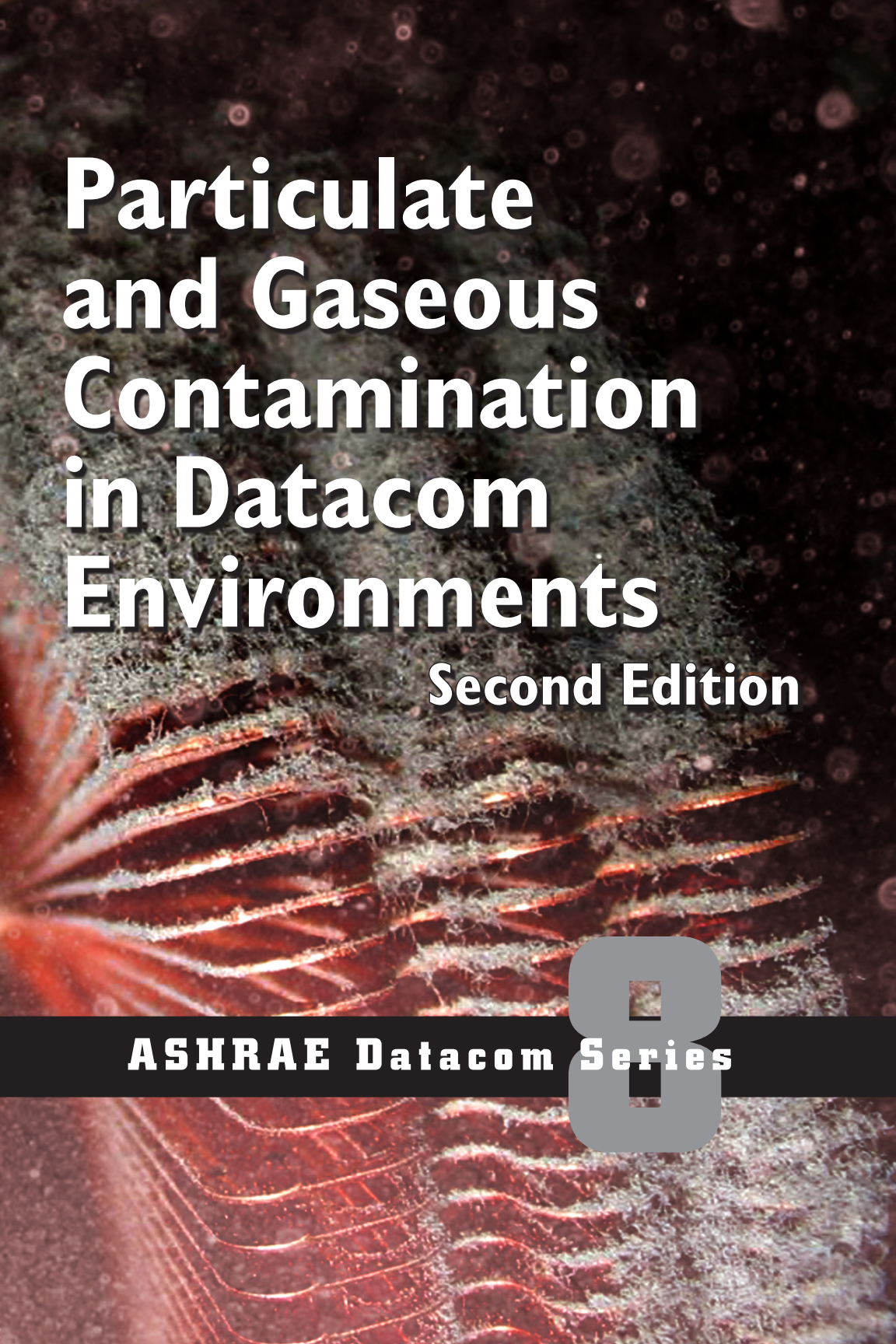

Particulate and Gaseous Contamination in Datacom Environments
Second Edition
ASHRAE Datacom Series
8

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Particulate and Gaseous Contamination in Datacom Environments

Second Edition

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Second Edition

ASHRAE Datacom Series
Book 8



Atlanta

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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

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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,

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- 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

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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

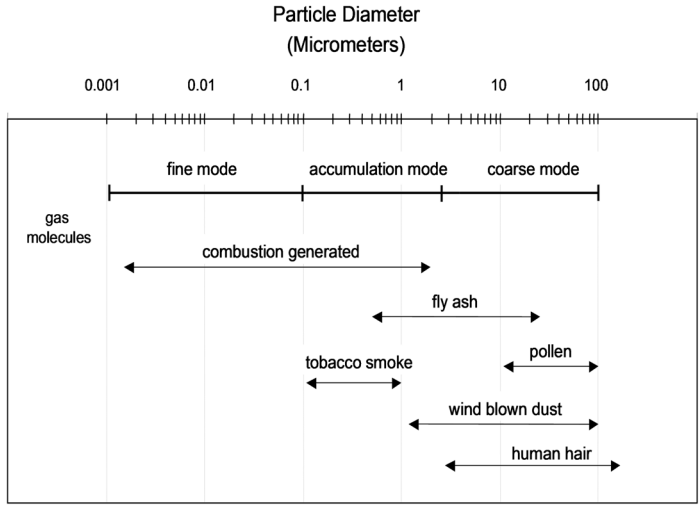
Particulate matter refers to airborne solid and liquid particles. For the purposes of this book, the terms particle, particulate, aerosol, and dust will be considered equivalent and all are represented by the term particulate matter. The size of particulate matter spans a vast range from about 0.001 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.

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I-P conversions:

$0.001\ \mu m = 3.94 \times 10^{-8}$ in.
$0.01\ \mu m = 3.94 \times 10^{-7}$ in.
$0.1\ \mu m = 3.94 \times 10^{-6}$ in.
$1\ \mu m = 3.94 \times 10^{-5}$ in.
$10\ \mu m = 3.94 \times 10^{-4}$ in.
$100\ \mu m = 3.94 \times 10^{-3}$ 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.

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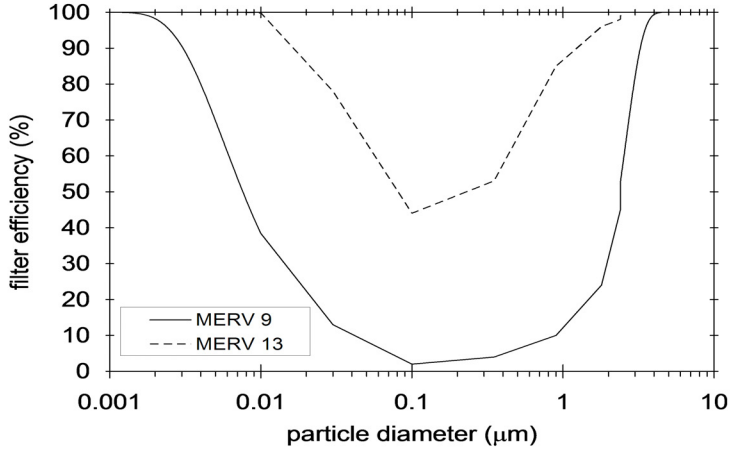


Figure 1.2 Filter efficiency of commonly used filters in datacom environments (Hanley et al. 1994; Riley et al 2002).

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

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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

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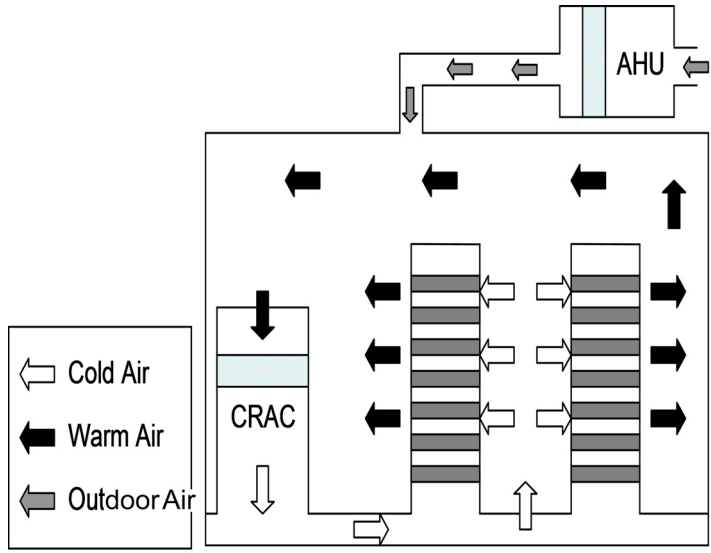


Figure 1.3 Airflow in a raised-access floor data center.

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.

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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.

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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

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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.

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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

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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.