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2011 Gaseous and Particulate Contamination Guidelines For Data Centers[1]

EXECUTIVE SUMMARY

Most data centers are well designed and are in areas with relatively clean environments, and most contamination is benign. Therefore, most data centers do not experience particulate or gaseous contamination-related information technology (IT) equipment failures. A small number of data centers, however, do. According to the major IT equipment manufacturers, the number of data centers with contamination-related failures is on the rise, though their numbers remain quite small.

In 2009, the IT manufacturer members of ASHRAE TC 9.9 authored a white paper (ASHRAE 2009a), titled "Particulate and Gaseous Contamination Guidelines for Data Centers," primarily targeted toward a minority of data centers that may have harmful environments resulting from the ingress of outdoor particulate and/or gaseous contamination. The document stated that for a small number of data centers, located mostly in the emerging markets, contamination can be a serious risk, and it provided insight into how to manage the contamination risk.

This white paper is an update to the original 2009 ASHRAE paper. The update is based on an ASHRAE survey of the air quality in data centers and on lessons learned in cleaning the air in contaminated data centers.

The reasons for the increasing number of data centers experiencing corrosion-related hardware failures are as follows:

- Change from lead-containing solder to lead-free solder, such as copper-tin-silver solder
- Changes in data center temperature and humidity operating conditions

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[1] This white paper on data center airborne contamination was prepared by ASHRAE TC 9.9, Mission Critical Facilities, Technology Spaces, and Electronic Equipment. The committee's members represent the following IT equipment manufacturers: AMD, Cisco, Cray, Dell, EMC, Hitachi, HP, IBM, Intel, Oracle, Seagate, and SGI. Helpful information for technical and nontechnical readers can be found in *Particulate and Gaseous Contaminants in Datacom Environments* (ASHRAE 2009b).

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- Continued miniaturizing of electronic components and ever-increasing circuit packaging density
- Proliferation of data centers into geographies with polluted environments

Two common modes of IT equipment failures due to environmental contamination are as follows:

- Copper creep corrosion on printed circuit boards
- Corrosion of silver termination in miniature surface-mounted components

Copper creep corrosion is the corrosion of copper plating to copper sulfide on printed circuit boards and the creeping of copper sulfide over the printed circuit boards, electrically shorting adjacent circuit-board features. The corrosion of silver termination, in surface-mounted components, to silver sulfide leads to the loss of silver metallization and eventual open circuiting of components such as resistors.

Data center contamination and its corrosive effects can be identified by well-defined and relatively easy means:

- Particulate (dust) contamination is characterized by its quantity and its corrosivity. The quantity of dust contamination can normally be identified by visual inspection of the IT equipment and by the filter replacement frequency. The corrosivity of the dust can be estimated by determining the deliquescent relative humidity, which is the relative humidity at which the dust becomes wet and, therefore, conductive (see Appendix B). Dust with high deliquescent relative humidity is generally more benign; dust with low deliquescent relative humidity is generally more corrosive. ASHRAE recommends that data centers be kept clean to ISO Class 8, which may be achieved simply by specifying the following means of filtration:
  - The room air may be continuously filtered with MERV 8 filters, as recommended by ASHRAE Standard 127 (ASHRAE 2007).
  - Air entering a data center may be filtered with MERV 11 or MERV 13 filters as recommended by ASHRAE (2009b).

For data centers utilizing free air cooling or air-side economizers, the choice of filters to achieve ISO class 8 level of cleanliness depends on the specific conditions present at that data center. In general, air entering a data center may require use of MERV 11 or, preferably, MERV 13 filters.

- Direct measurement of gaseous contamination levels is difficult and is not a useful indicator of the suitability of the environment for IT equipment. A low-cost, simple approach to monitoring the air quality in a data center is to expose copper and silver foil coupons in the data center for 30 days followed by coulometric reduction analysis in a laboratory to determine the thickness of the corrosion products on the metal coupons. ASHRAE recommends that data center operators maintain an environment with corrosion rates within the following guidelines:

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- Copper reactivity rate of less than 300 Å/month
- Silver reactivity rate of less than 200 Å/month

Following this guideline will help ensure reliable equipment operation.

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. Gas-phase filtration systems are commercially available.

INTRODUCTION

The objective of this white paper is to describe the need to control airborne contaminants, both particulate and gaseous, in data centers and to specify their recommended acceptable limits.

The ever-improving performance of computers is being accomplished by decreasing the size of the transistors and the distances electrical signals have to travel to accomplish the tasks assigned to them. The net effect is the miniaturizing of all electronic components and their ever-increasing packaging density, which may have the following detrimental effects on hardware reliability:

- The increased heat load per unit volume in some cases necessitates the need for more airflow to maintain hardware within acceptable temperature limits. The increased airflow increases the exposure of the electronics to the detrimental effects of accumulated dust and to the increased intake of gaseous contaminants.
- The higher packaging density does not always allow the hermetic sealing of components, further exposing electronics to the detrimental effects of moisture, dust, and gaseous contaminations.
- The decreased spacing between printed circuit board features at different voltages increases the possibility of dust and gases causing ion migration and/or creep corrosion leading to electrical short circuiting.
- As the features in the components approach the sizes of the corrosion products, the components become more prone to the ill effects of corrosion.

The recent increase in the rate of hardware failures in data centers high in sulfur-bearing gases, highlighted by the number of publications on the subject (Reid et al. 2007; Cullen and O'Brien 2004; Veale 2005; Sahu 2007; Schueller 2007; Hillman et al. 2007; Xu et al. 2007; Mazurkiewicz 2006), led to the need for the 2009 white paper that recommended that in addition to temperature-humidity control, dust and gaseous contamination should also be monitored and controlled. The additional environmental measures recommended in the 2009 white paper are necessary to reduce the two most common recent failure modes of copper creep corrosion on circuit boards and the corrosion of silver metallization in miniature surface mounted components:

- Papers have recently reported copper creep corrosion on circuit boards (Cullen and O'Brien 2004; Mazurkiewicz 2006; Mukadam et al. 2006; Schueller

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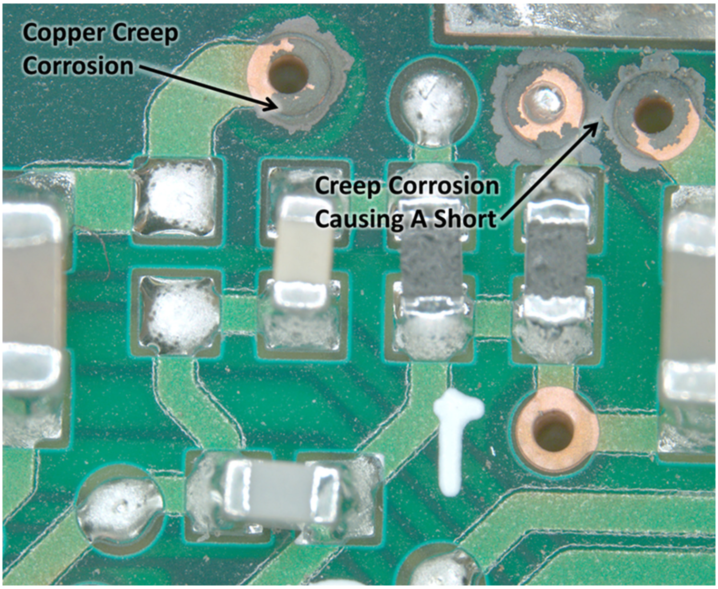

Figure 1 Example of copper creep corrosion on a lead-free circuit board.

2007; Xu et al. 2007). The two common circuit board types suffering from copper creep corrosion are those with an immersion silver (ImAg) finish and, to a lesser extent, those with an organic solderability preservative (OSP) coating. The sulfur-bearing gases and moisture can corrode any exposed copper metallization on the circuit board. The resulting corrosion product, copper sulfide, can creep over the circuit board and short circuit closely spaced features, as shown in Figure 1.

- Some recent papers have reported corrosion of miniature surface-mounted components that contain silver (Hillman et al. 2007; Reid et al. 2007). Sulfur-bearing gases—even in the absence of moisture—attack silver, forming silver sulfide corrosion products that, being larger in volume, create mechanical stresses which undermine the integrity of the package. With the integrity of the package breached, the underlying silver is exposed to further corrosive attack, until all the silver in the section is consumed, leading to an electrical open. The silver sulfide corrosion product on the field-failed hardware is often visible under a low-power microscope as needles or nodules, as shown in Figure 2.

It should be noted that the reduction of circuit board 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 ever-shrinking hardware. Therefore, the need to control data center

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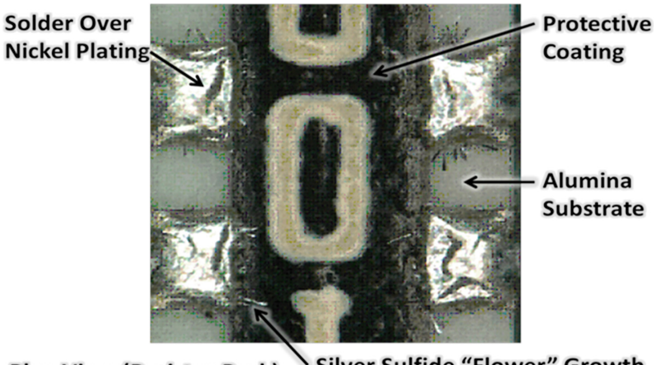
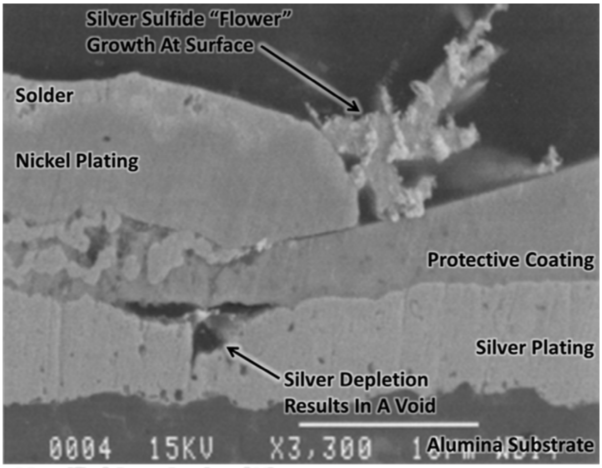


Plan View (Resistor Pack)



Magnified Cross Sectional View

Figure 2 (Top) plan view and (bottom) magnified cross-sectional view of an example of a component failure due to an environment high in sulfur-bearing gases attacking the silver metallization in the component, producing silver sulfide "flowers."

airborne contaminants and to specify their recommended acceptable limits is becoming critical to the continued reliable operation of IT equipment.

AIRBORNE DUST

Failure modes due to dust include but are not limited to the following (ASHRAE 2009b):

- *Mechanical effects.* Mechanical effects include obstruction of cooling airflow, interference with moving parts, abrasion, optical interference, interconnect

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interference, or deformation of surfaces (e.g., magnetic media) and other similar effects.

- *Chemical effects.* Dust settled on printed circuit boards can lead to component corrosion and/or to the electrical short circuiting of closely spaced features.
- *Electrical effects.* Electrical effects include impedance changes and electronic circuit conductor bridging.

Dust is ubiquitous. Even with the best filtration efforts, dust will be present in a data center and will settle on electronic hardware. Fortunately, most dust is benign. Only under rare circumstances will dust degrade electronic hardware.

Harmful dust in data centers is generally high in ionic content, such as sulfur- and chlorine-bearing salts. The source of this harmful dust is mainly outdoor dust in the size range 2.5–15 μm for coarse dust and 0.1–2.5 μm for fine dust (Comizzoli et al. 1993). Coarse dust particles have a mineral and biological origin, are formed mostly by wind-induced abrasion, and can remain airborne for a few days. Fine dust particles are generally the result of fossil-fuel burning and volcanic activity and can remain airborne for years. Large bodies of salt water are also a major source of airborne dust contamination in data centers. Sea salt can be carried 10 km (6 mi) inland or farther by high winds present in coastal areas and can damage electronic devices at this range (Bennett et al. 1999; Crossland and Wright 1973).

One mechanism by which dust degrades the reliability of printed circuit boards involves the absorption of moisture from the environment by the settled dust. The ionic contamination in the wet dust degrades the surface insulation resistance of the printed circuit board and, in the worst-case scenario, leads to electrical short circuiting of closely spaced features via ion migration. Figure 3 shows an example of copper corrosion caused by dust settled on a printed circuit board.

Deliquescent relative humidity, the relative humidity at which the dust absorbs enough water to become wet and promote corrosion and/or ion migration, determines the corrosivity of dust. When the deliquescent relative humidity of dust is greater than the relative humidity in the data center, the dust stays dry and does not contribute to corrosion or ion migration. However on the rare occurrence when the dust has deliquescent relative humidity lower than the relative humidity in the data center, the dust will absorb moisture, get wet, and promote corrosion and/or ion migration, thereby degrading hardware reliability. A study by Comizzoli et al. (1993) for various locations worldwide showed that leakage current due to dust that settled on printed circuit boards increased exponentially with relative humidity. This study leads us to the conclusion that keeping the relative humidity in a data center below about 60% will keep the leakage current from settled fine dust within the acceptable sub-μA range.

Under rare circumstances, harmful dust can also be generated within a data center. Humidifiers that depend on airborne water droplets evaporating to control the humidity in the room may increase the levels of harmful indoor dust pollution if the water feeding the humidifier is high in salts that have lower deliquescent relative humidity than the relative humidity in data centers. Even low concentrations of these salts can be serious corrosion and ion migration threats. These humidifier-related

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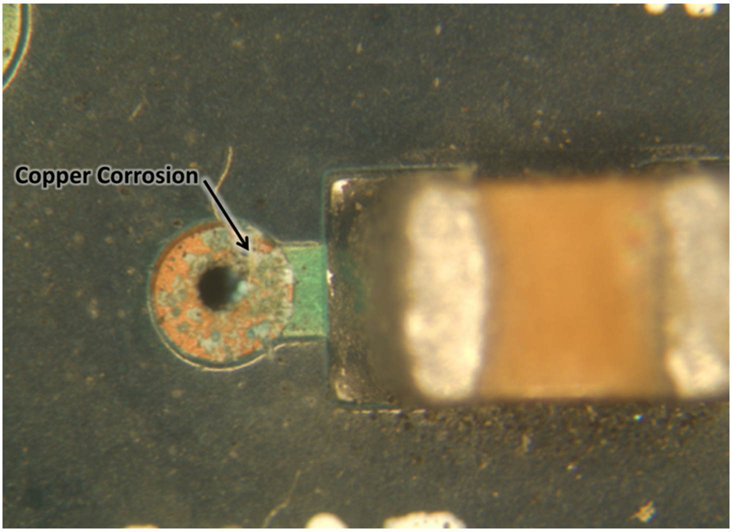

Figure 3 Corrosion of a plated through hole because of wetted ionic dust high in magnesium chloride.

corrosion problems can be mitigated by treating the humidifier water using reverse osmosis (ASHRAE 2009b).

Fibrous dust from paper, cardboard, and textiles can foul heat sinks and disrupt equipment cooling. Every effort should be made to avoid working with large amounts of these materials within data centers. For instance, new equipment should be unboxed outside of the data center, and high-volume printers should be located elsewhere.

In summary, most dust is benign. Corrosion and/or ion migration problems may arise under rare circumstances when the settled dust has deliquescent relative humidity lower than the relative humidity in the data center. As a general rule, the relative humidity in a data center should be kept below 60% to avoid dust corroding the hardware.

Another form of particulate contamination very detrimental to hardware reliability is zinc whiskers, which are the most common electrically conductive particles found in data centers. The undersides of some steel raised-floor tiles are coated with zinc to prevent corrosion. The stringers and pedestals supporting the tiles may also be coated with zinc. Zinc may be electroplated or hot-dip galvanized. Although zinc whiskers may grow on both types of coatings, electroplated zinc is far more susceptible to whisker growth (Brusse and Sampson 2004; Lahtinen and Gustafsson 2005).

Zinc whiskers, which may sometimes grow to 1–2 mm (0.04–0.08 in.) in length, threaten IT equipment when they become dislodged and airborne, which could happen when the tiles are disturbed during their removal or when pulling or removing underfloor cables. If zinc whiskers are ingested by IT equipment, circuits with

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voltages higher than about 25 V may suffer electrical short circuiting, arcing, signal perturbations, or catastrophic failures (Miller 2007).

A simple method to detect zinc whiskers is with the use of a flashlight. Remove a raised-floor tile and place the tile on its edge in a dimly lit area. Shine the flashlight across the underside of the tile at a 45° angle. Small speckles that twinkle in the bright light may be evidence of zinc whiskers. To confirm the presence of zinc whiskers, specimens should be collected using carbon adhesive tabs and viewed in a scanning electron microscope. If zinc whiskers are present, remediation involves replacing the contaminated raised-floor tiles and hiring professionals to clean the data center.

ISO 14644-1 has become the dominant, worldwide standard for classifying the cleanliness of air in terms of concentration of airborne particles (ISO 1999). Table 1 provides maximum concentration levels for each ISO class (ASHRAE 2009b).

ASHRAE recommends that data centers be kept clean to ISO Class 8 with the strictness of the 95% upper confidence limit (Ortiz 2006). For data centers without economizers, the ISO class 8 cleanliness level may be achieved simply by specifying the following means of filtration:

- The room air may be continuously filtered with MERV 8 filters as recommended by ASHRAE Standard 127 (ASHRAE 2007).
- Air entering a data center may be filtered with MERV 11 or MERV 13 filters as recommended by ASHRAE (2009b).

For data centers utilizing free air cooling or air-side economizers, the choice of filters to achieve ISO class 8 level of cleanliness depends on the specific conditions present at that data center. In general, air entering a data center may require use of MERV 11 or, preferably, MERV 13 filters.

GASEOUS CONTAMINATION

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 et al. 1981). An example of corrosion, due to gaseous contamination, on a circuit board compliant with the Restriction of Hazardous Substances Directive (RoHS) (EU 2003) is shown in Figure 1.

Gaseous composition environmental limits have been published in ISA-71.04 (ISA 1985). These limits serve as guides for specifying data center environmental cleanliness, but they are not useful for surveying the corrosivity or predicting the failure rates of hardware in the data center environment 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 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 copper, but the combination of these gases with other gases such as nitrogen dioxide (NO_2) and/or ozone (O_3) are very corrosive (Volpe 1989). The corrosion rate of copper is a strong function of relative

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Table 1 ISO 14644-1 (ISO 1999) Air Cleanliness Classification vs. Maximum Particle Concentrations Allowed (particles/m^3)

ISO CLASS	Maximum Number of Particles in Air (Particles in Each Cubic Meter Equal to or Greater Than the Specified Size)					
	Particle size, μm					
	>0.1	>0.2	>0.3	>0.5	>1	>5
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 measurements process require that data with no more than three (3) significant figures be used in determining the classification level.

humidity, while the corrosion rate of silver has lesser dependence on humidity (Rice et al. 1981).

A very convenient and quantitative way to determine the corrosivity of air in a data center is the so called "reactive monitoring" method described in ISA-71.04 (ISA 1985). This method exposes a copper coupon 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, described in Table 2. According to ISA-71.04, 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 in determining equipment reliability. But the use of copper coupon alone has two major limitations: One is that copper is not sensitive to chlorine, a contaminant particularly corrosive to many metals, and the other is that 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. It is now common practice to include silver coupons along with copper coupons to gain greater insight into the chemistry of the corrosive gases in the environment.

The 2009 ASHRAE particulate and gaseous contamination white paper recommended that copper and silver corrosion rates should be less than 300 Å/month to minimize the impact of corrosion on IT equipment reliability. This position was based partly on an unpublished survey that compared the copper and silver corrosion

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Table 2 Gaseous Corrosivity Levels per ISA-71.04 (ISA 1985)

Severity Level	Copper Reactivity Level, Å/month	Description
G1 Mild	300	An environment sufficiently well-controlled such that corrosion is not a factor in determining equipment reliability.
G2 Moderate	300–1000	An environment in which the effects of corrosion are measurable and may be a factor in determining equipment reliability.
G3 Harsh	1000–2000	An environment in which there is high probability that corrosive attack will occur.
GX Severe	>2000	An environment in which only specially designed and packaged equipment would be expected to survive.

rates in data centers with and without reported corrosion-related hardware failures. The study concluded that the data centers with copper and silver corrosion rates <300 Å/month had a low probability of corrosion-related hardware failures and that silver corrosion rate is a better indicator than copper corrosion rate of the reliability impact of gaseous contamination (Singh et al. 2009).

In mid-2010, some members of ASHRAE TC 9.9, representing the IT equipment manufacturers, started a year-long survey of equal numbers of data centers with and without corrosion-related hardware failures. The results of the survey thus far are shown in Figure 4. The silver corrosion rates in data centers that have reported corrosion-related hardware failures rates are above about 200 Å/month; whereas, those with no reported corrosion-related hardware failures have 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 show significant overlap, though in general the copper corrosion rates are higher in data centers with corrosion-related hardware failures. The ASHRAE data center survey will continue for a few more months, but there is enough evidence to conclude that the maximum corrosion rate of silver should be reduced to 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 all year round, but as a data center's history increases, monitoring may be limited to the months with known high levels of gaseous contamination. The reactive monitoring method requires that the copper coupons and silver coupons be exposed for one month in order to obtain a good measure of the corrosivity of the environment. Air-side economizers increase the reliability risk in data centers. 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.

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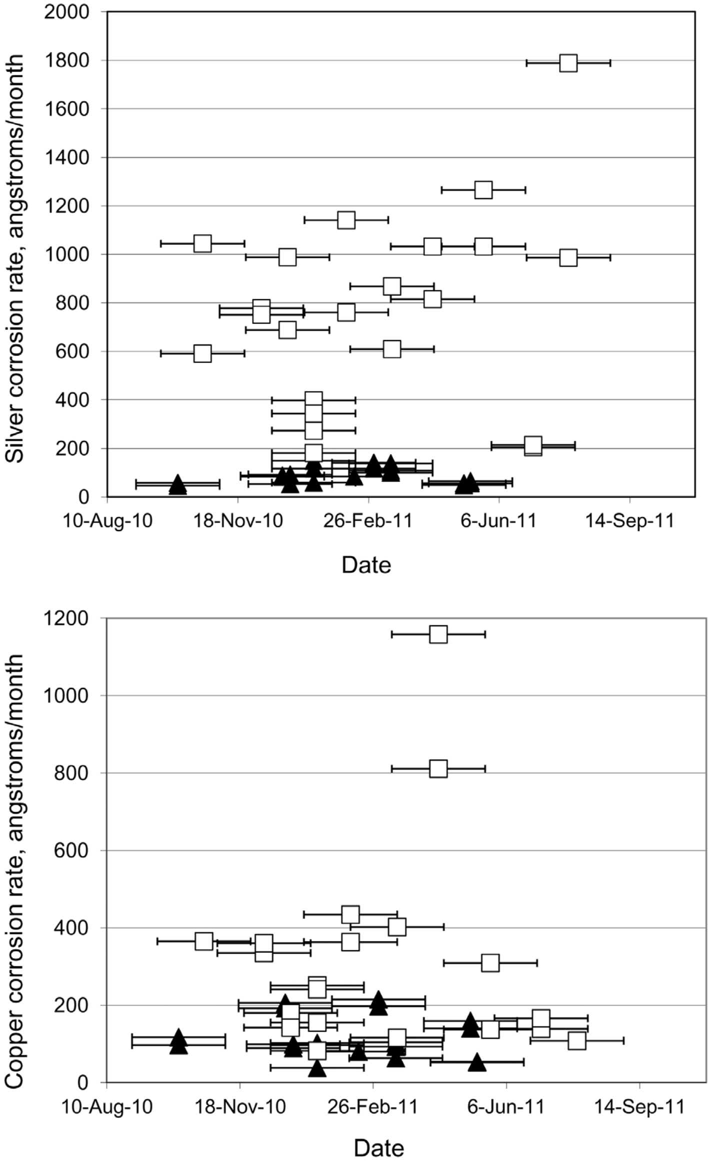

Figure 4 The open square data points are for data centers with known corrosion-related hardware failures. The solid triangle data points are for data centers with no known corrosion-related hardware failures. Notice that the silver corrosion rates for data centers with and without corrosion-related hardware failures show no overlap; whereas, the copper corrosion rates for the two types of data centers show some overlap.

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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. Two types of real-time reactive monitors are commercially available. One is based on measuring the rate of increase of corrosion product mass using a quartz crystal microbalance. The other determines gaseous corrosivity by measuring the rate of electrical resistance increase of metal thin films.

Figure 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. Notice the association between the silver corrosion rate and the concentrations of SO_2 and NO_2 and fine dust in the outdoor air. The silver corrosion rate (slope of corrosion product thickness versus time in top plot of Figure 5) is very low between noon and 8 p.m. and high (approximately 2500 Å/month) between 8 p.m. and noon the next day. 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, such as shutting off outside corrosive air from entering the data center.

GAS-PHASE FILTRATION OF AIR IN DATA CENTERS

For data centers with or without air-side economizers that do not fall within the modified ISA-71.04 (ISA 1985) severity level G1 for copper (<300 Å/month) and silver (<200 Å/month) corrosion, gas-phase filtration is recommended. The blowers at the air inlet, fitted with particulate and gas-phase filters, can be used to fill the data center with clean air and to pressurize it to prevent contaminated outdoor air from leaking into the data center. The air in the data center can be recirculated through gas-phase filters to remove contaminants that are generated within the data center. With these measures, it is recommended that the level of gaseous contaminants be brought within the modified ISA-71.04 severity level G1 for copper and silver corrosion.

The result of a recent example of implementation of gas-phase filtration in a contaminated data center is shown in Figure 6. The silver corrosion rate of about 1000 Å/month was brought down to levels well below 100 Å/month by pressurizing the data center with gas-phase filtered air and by replacing the particle filters in the computer room air conditioners with gas-phase filters. Notice that the copper corrosion rates in this data center, like those in many other data centers with reported hardware corrosion, were well within the ISA-71.04 (ISA 1985) severity level G1.

THERMAL GUIDELINES FOR DATA PROCESSING ENVIRONMENTS—EXPANDED DATA CENTER CLASSES AND USAGE GUIDANCE

ASHRAE TC 9.9 published the supplemental white paper, "2008 ASHRAE Environmental Guidelines for Datacom Equipment—Expanding the Recommended Envelope" and updated it in 2011 to provide greater flexibility in facility operations, particularly with the goal of reduced energy consumption in data centers, by expanding the recommended operating temperature-humidity environmental envelope (ASHRAE 2008, 2011).

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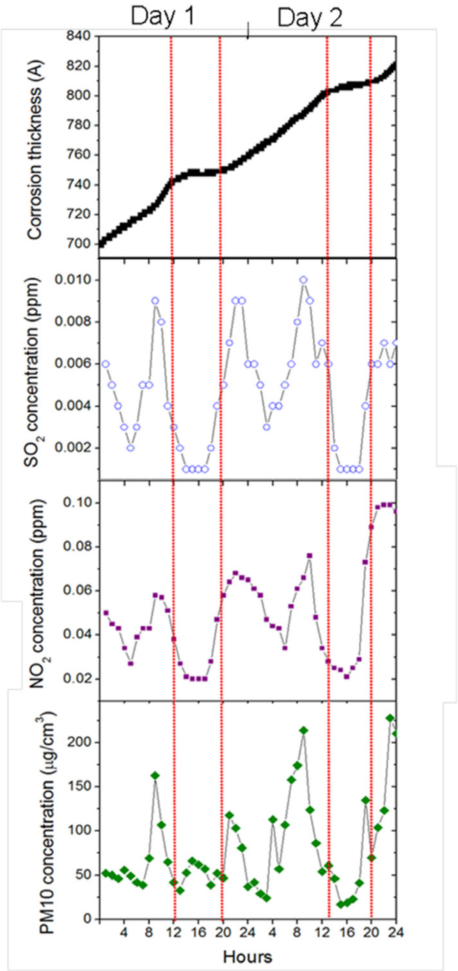

Figure 5 Silver corrosion thickness, SO_2, NO_2, and dust level as a function of time of day in a data center.

The purpose of the recommended envelope is to give guidance to data center operators on maintaining high reliability and operating their data centers in the most energy efficient manner.

In addition to the recommended envelope is the allowable envelope in which IT manufacturers verify that their equipment will function. Typically, manufacturers perform a number of tests prior to announcement of a product to verify that it meets all the functionality requirements within the allowable environmental envelope. This is not a statement of reliability but one of functionality of the IT equipment. However, the recommended envelope *is* a statement on reliability.

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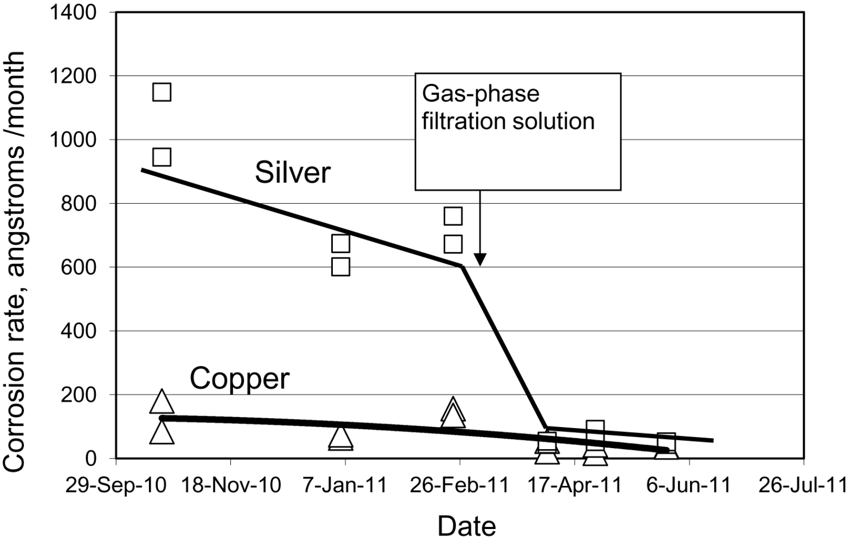

Figure 6 Gas-phase filtration solution to a contaminated data center.

For extended periods of equipment operation, the IT manufacturers recommend that data center operators maintain their environment within the recommended envelope. Exceeding the recommended limits for short periods of time should not be a problem, but running near the allowable limits for months could result in increased reliability issues.

In reviewing the available data from a number of IT manufacturers, the 2008 and 2011 expanded recommended operating envelope is the agreed-upon envelope that is acceptable to all the IT manufacturers, and operation within this envelope will not compromise overall reliability of the IT equipment. The previous recommended envelope data are shown in Table 3.

The ranges apply to the inlets of all equipment in the data center, except where IT manufacturers specify other ranges. Attention is needed to make sure the appropriate inlet conditions are achieved for the top portion of IT equipment racks. The inlet air temperature in many data centers tends to be warmer at the top portion of racks, particularly if the warm rack exhaust air does not have a direct return path to the air-handling units. This warmer air also affects the relative humidity, resulting in lower values at the top portion of the rack.

The recommended upper limit of 60% relative humidity in the 2008 and 2011 white papers on thermal guidelines for data processing environments arises from the following:

- Corrosion products, such as oxides, may form and protect the metal and slow down the corrosion rate. In the presence of gaseous pollutants, such as SO_2

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Table 3 ASHRAE Recommended Environment for Temperature and Moisture (ASHRAE 2008, 2011)

	2004 Version	2008/2011 Version
Low-end temperature	20°C (68°F)	18°C (64.4°F)
High-end temperature	25°C (77°F)	27°C (80.6°F)
Low-end moisture	40% relative humidity	5.5°C (41.9°F) dew point
High-end moisture	55% relative humidity	60% relative humidity and 15°C (59°F) dew point

and H_2S, and ionic pollutants, such as chlorides, the corrosion-product films are less protective, allowing corrosion to proceed somewhat linearly. When the relative humidity in the data center is greater than the deliquescent relative humidity of the corrosion products, such as copper sulfate, cupric chloride, and the like, the corrosion-product films get wet, dramatically increasing the rate of corrosion. Cupric chloride, a common corrosion product on copper, has a deliquescent relative humidity of about 65%. In a data center with relative humidity greater than 65%, the cupric chloride would absorb moisture, get wet, and aggravate the copper corrosion rate.

- Dust is ubiquitous. Even with our best filtration efforts, fine dust will be present in a datacenter and will settle on electronic hardware. Fortunately, most dust has particles with high deliquescent relative humidity, which is the relative humidity at which the dust absorbs enough water to become wet and promote corrosion and/or ion migration. When the deliquescent relative humidity of dust is greater than the relative humidity in the data center, the dust stays dry and does not contribute to corrosion or ion migration. However on the rare occurrence when the dust has deliquescent relative humidity lower than the relative humidity in the datacenter, the dust will absorb moisture, get wet, and promote corrosion and/or ion migration, degrading hardware reliability. A study by Comizzoli et al. (1993) for various locations worldwide showed that leakage current due to dust that settled on printed circuit boards increased exponentially with relative humidity. This study leads us to the conclusion that keeping the relative humidity in a data center below about 60% will keep the leakage current from settled fine dust in the acceptable sub-µA range.

In summary, mission-critical data center equipment should be protected from corrosion by keeping the relative humidity below 60% and by limiting the particulate and gaseous contamination concentration to levels at which the copper corrosion rate is <300 Å/month and the silver corrosion rate is <200 Å/month. The less than 60% relative humidity requirement may be relaxed in clean data centers relatively free of sulfur-bearing gaseous contamination and particulate contamination with high deliquescent relative humidity.

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Given these reliability concerns, data center operators need to pay close attention to the overall data center humidity and local condensation concerns, especially when running economizers on hot/humid summer days. When operating in polluted geographies, data center operators must also consider particulate and gaseous contamination, because the contaminants can influence the acceptable temperature and humidity limits within which data centers must operate to keep corrosion-related hardware failure rates at acceptable levels. Dehumidification, filtration, and gas-phase filtration may become necessary in polluted geographies with high humidity.

SUMMARY

The recent increase in the rate of hardware failures in data centers high in sulfur-bearing gases—due to copper creep corrosion on printed circuit boards and corrosion of silver in some miniature surface mount components—highlighted by the number of recent publications on the subject, led to the need for the original 2009 white paper on particulate and gaseous contamination in data centers that recommended that in addition to temperature-humidity control, dust and gaseous contamination should also be monitored and controlled. These additional environmental measures are especially important for data centers located near industries and/or other sources that pollute the environment.

It is incumbent on data center managers to do their part in maintaining hardware reliability by monitoring and controlling dust and gaseous contamination in their data centers. Data centers must be kept clean to Class 8 of ISO 14644-1 (ISO 1999). This level of cleanliness can generally be achieved by an appropriate filtration scheme, as outlined in the following:

- The room air may be continuously filtered with MERV 8 filters as recommended by ASHRAE Standard 127 (2007a).
- Air entering a data center may be filtered with MERV 11 to MERV 13 filters as recommended in *Particulate and Gaseous Contamination in Datacom Environments* (ASHRAE 2009b).

Sources of dust inside data centers should be reduced. Every effort should be made to filter out dust that has deliquescent relative humidity less than the maximum allowable relative humidity in the data center.

The gaseous contamination should be within the modified severity level G1 of ISA-71 (ISA 1985) that meets

- a copper reactivity rate of less than 300 Å/month, and
- 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 IT equipment and avoid the cost of hardware replacement not covered under warranty. For a summary of recommendations, see Table 4.

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Table 4 Summary of Recommended Acceptable Environmental Limits

Recommended Operating Environment[1, 3]

Temperature	18°C (64.4°F) to 27°C (80.6°F)[3]
Low-end moisture	5.5°C (41.9°F) dew point
High-end moisture	60% relative humidity or 15°C (59°F) dew point
Gaseous contamination	Severity level G1 as per ISA 71.04 (ISA 1985) which states that the reactivity rate of copper coupons shall be less than 300 Å/month (= 0.0039 $\mu\text{g/cm}^2\cdot\text{h}$ weight gain)[5]. In addition, the reactivity rate of silver coupons shall be less than 200 Å/month (= 0.0024 $\mu\text{g/cm}^2\cdot\text{h}$ weight gain)[6]. The reactive monitoring of gaseous corrosivity should be conducted approximately 2 in. (5 cm) in front of the rack on the air inlet side, at one-quarter and three-quarter frame height off the floor or where the air velocity is much higher.
Particulate contamination	1. Data centers with or without air-side economizers must meet the cleanliness level of ISO class 8. 2. The deliquescent relative humidity of the particulate contamination should be more than 60%[2]. 3. Data centers must be free of zinc whiskers[4]. 4. For data center without air-side economizer, the ISO class 8 cleanliness may be met simply by the choice of the following filtration: a. The room air may be continuously filtered with MERV 8 filters b. Air entering a data center may be filtered with MERV 11 or preferably MERV 13 filters. 5. For data centers with air-side economizers, the choice of filters to achieve ISO class 8 cleanliness depends on the specific conditions present at that data center. In general, air entering a data center may require to be filtered using MERV 11 or preferably MERV 13 filters.

Recommended Non-Operating Environment[3]

Temperature	10°C–43°C (50°F–109.4°F)
Relative humidity	8% to 80%
Wet bulb	Less than 23°C (73°F)
Gaseous contamination	Severity level G1 as per ISA 71.04 (ISA 1985) which states that the reactivity rate of copper coupons shall be less than 300 Å/month (=0.0039 $\mu\text{g/cm}^2\cdot\text{hour}$ weight gain)[5]. In addition, the reactivity rate of silver coupons shall be less than 200 Å/month (= 0.0024 $\mu\text{g/cm}^2\cdot\text{hour}$ weight gain)[6]. The reactive monitoring of gaseous corrosivity should be conducted approximately 2 in. (5 cm) in front of the rack on the air inlet side, at one-quarter and three-quarter frame height off the floor. Note that since gaseous corrosivity is a function of air velocity, measuring corrosivity in front of a non-operating machine with no airflow will give lower corrosivity reading than if the machine was operating.

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Table 4 Summary of Recommended Acceptable Environmental Limits

Recommended Non-Operating Environment[3] (continued)	
Particulate contamination	6. Data centers with or without air-side economizers must meet the cleanliness level of ISO class 8. 7. The deliquescent relative humidity of the particulate contamination should be more than 60%[2]. 8. Data centers must be free of zinc whiskers[4]. 9. For data center without air-side economizer, the ISO class 8 cleanliness may be met simply by the choice of the following filtration: a. The room air may be continuously filtered with MERV 8 filters b. Air entering a data center may be filtered with MERV 11 or preferably MERV 13 filters. 10. For data centers with air-side economizers, the choice of filters to achieve ISO class 8 cleanliness depends on the specific conditions present at that data center. In general, air entering a data center may require to be filtered using MERV 11 or preferably MERV 13 filters.

Notes:

1. Gaseous contamination is measured approximately 2 in. (5 cm) in front of the rack on the air inlet side, at one-quarter and three-quarter frame height off the floor. Derate the maximum recommended ambient temperature by 1°C (1.8°F) for every 300 m (984 ft) over 1800 m (5906 ft). For extended periods of time, IT manufacturers recommend that data center operators maintain the recommended envelope for maximum reliability. The allowable envelope is where IT manufacturers test their equipment in order to verify that the equipment will function. This is not a statement of reliability, but one of functionality of the IT equipment.
2. The deliquescent relative humidity of particulate contamination is the relative humidity at which the dust absorbs enough water to become wet and promote corrosion and/or ion migration.
3. The machine should be in an environment that satisfies the recommended operating environment specification for at least one day before it is powered on.
4. Surface debris is randomly collected from 10 areas of the data center on a 1.5-cm diameter disk of sticky electrically conductive tape on a metal stub. If examination of the sticky tape in a scanning electron microscope reveals no zinc whiskers, the data center is considered free of zinc whiskers.
5. The derivation of the equivalence between the rate of copper corrosion product thickness growth in Å/month and the rate of weight gain assumes that Cu_2S and Cu_2O grow in equal proportions.
6. The derivation of the equivalence between the rate of silver corrosion product thickness growth in Å/month and the rate of weight gain assumes that Ag_2S is the only corrosion product.

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APPENDIX A—
RELATIONSHIP OF µg/cm²·h AND Å/30 DAYS CORROSION RATES FOR COPPER AND SILVER

Papers on atmospheric corrosion of metals often report corrosion rates in terms of rate of weight gain in $\mu g/cm^2 \cdot h$. ISA Standard 71.04 (ISA 1985) reports corrosion rates in terms of the rate of increase of corrosion product thickness in Å/month.

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/cm^3.

Silver specimen weight gain of

$$\begin{aligned} 1\,\mu g &\equiv \frac{2 \times 107.9 + 32}{32}\,\mu g \text{ of } Ag_2S \\ &\equiv 7.74 \times 10^{-6} \text{ g of } Ag_2S \\ &\equiv \frac{7.74 \times 10^{-6}}{7.23} \text{ cm}^3 \text{ of } Ag_2S \\ &\equiv 1.07 \times 10^{-6} \text{ cm}^3 \text{ of } Ag_2S \end{aligned}$$

$$\begin{aligned} 1\ \mu g/cm^2 \cdot h &\equiv 1.07 \times 10^{-6} \text{ cm/h} \\ &\equiv 1.07 \times 10^{-6} \times 10^{8} \text{ Å/h} \\ &\equiv 107 \times 24 \times 30 \text{ Å/30 days} \\ &\equiv 7.7 \times 10^{4} \text{ Å/30 days} \end{aligned}$$

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If we assume that the silver corrosion product is mostly Ag_2S, then 200 Å/month rate of corrosion product growth is equivalent to 0.0026 $\mu g/cm^2{\cdot}h$ 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

$$\begin{aligned} 1\,\mu g &\equiv \frac{2\times 63.55+32}{32}\mu g \text{ of } Cu_2S \\ &\equiv 5\times 10^{-6}\text{ g of } Cu_2S \\ &\equiv \frac{5\times 10^{-6}}{5.6}\text{ cm}^3\text{of } Cu_2S \\ &\equiv 0.9\times 10^{-6}\text{ cm}^3\text{ of } Cu_2S \end{aligned}$$

$$\begin{aligned} 1\ \mu g/cm^2{\cdot}h &\equiv 0.9\times 10^{-6}\text{ cm/h} \\ &\equiv 0.9\times 10^{-6}\times 10^{8}\text{ Å/h} \\ &\equiv 90\times 24\times 30\text{ Å/30 days} \\ &\equiv 6.4\times 10^{4}\text{ Å/30 days} \end{aligned}$$

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

$$\begin{aligned} 1\,\mu g &\equiv \frac{2\times 63.55+16}{16}\mu g \text{ of } Cu_2O \\ &\equiv 8.94\times 10^{-6}\text{ g of } Cu_2O \\ &\equiv \frac{8.94\times 10^{-6}}{6}\text{ cm}^3\text{of } Cu_2O \\ &\equiv 1.5\times 10^{-6}\text{ cm}^3\text{ of } Cu_2O \end{aligned}$$

$$\begin{aligned} 1\ \mu g/cm^2{\cdot}h &\equiv 1.5\times 10^{-6}\text{ cm/h} \\ &\equiv 1.5\times 10^{-6}\times 10^{8}\text{ Å/h} \\ &\equiv 1.5\times 10^{2}\times 24\times 30\text{ Å/30 days} \\ &\equiv 10.8\times 10^{4}\text{ Å/30 days} \end{aligned}$$

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 follows:

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

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 B—
MEASURING THE DELIQUESCENT RELATIVE HUMIDITY OF DUST

Dust should be lifted off the easily accessible surfaces of the computers in the data center, collected in clean plastic bags, and shipped to an analysis laboratory. The dust should be sprinkled on the interdigitated areas of a surface insulation resistance (SIR) test circuit board (part number IPC-B-24 obtained from IPC vendors listed in the website http://www.ipc.org/ContentPage.aspx?pageid=Test-Board-Vendors) shown in Figure B1. The spacing between the interdigitated combs is 0.5 mm (0.02 in.). The sprinkled dust should bridge the 0.5 mm gap. The circuit board should then be placed in a humidity chamber with a starting relative humidity of about 20% at room temperature and a 10 V bias applied across the interdigitated combs. The relative humidity should be raised at a constant rate from 20% to 90% over the period of a week and the leakage current between the interdigitated combs plotted as a function of time. The relative humidity at which the leakage current rises sharply is the deliquescent relative humidity of the dust.

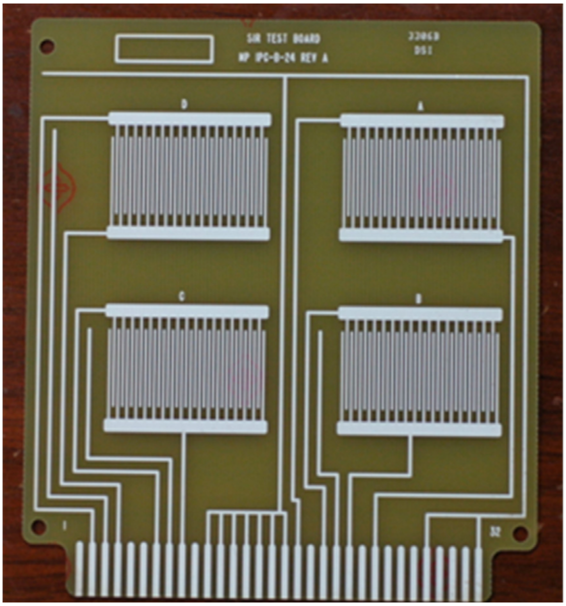

Figure B1 Test circuit board (part number IPC-B-24).