Part 1:

Gaseous and Particulate Contamination Limits for Data Centers

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Abstract

The recent increase in the failure rates of mission-critical IT equipment in data centers high in sulfur-bearing gases, highlighted by the number of recent publications on the subject, led the ASHRAE TC 9.9 committee to publish a white paper that recommended that in addition to temperature and humidity, 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 circuit boards and the corrosion of silver metallization in miniature surface mounted components. It is incumbent on the data center managers to do their part in maintaining hardware reliability by monitoring and controlling the dust and gaseous contamination in their data centers. Every effort should be made to filter out dust to ISO 14644-1 Class 8, especially if dust has deliquescent relative humidity greater than the maximum allowable relative humidity in the data center. The gaseous contamination should be kept within the modified ANSI/ISA-71.04-1985 severity level G1 that specifies the copper and silver corrosivity rates of < 30 nm/month.

Introduction

This article is based on a 2009 ASHRAE Technical Committee (TC) 9.9 white paper that describes the need to control airborne contaminants, both particulate and gaseous, in data centers and specifies their recommended acceptable limits (ASHRAE 2009a).

The ever increasing 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 them. The net effect is the miniaturizing of electronic components and their ever increasing packaging density with the following detrimental effects on hardware reliability:

- The increased heat load per unit volume necessitates the need for more air flow to maintain hardware within acceptable temperature limits. The increased air flow increases the exposure of the electronics to the detrimental effects of accumulated dust and the increased ingestion of gaseous contaminates.
- 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 contamination.
- The decreased spacing between printed circuit board features at different voltages increases the possibility of dust and gases causing ion migration leading to electrical short circuiting.
- As the features in the components

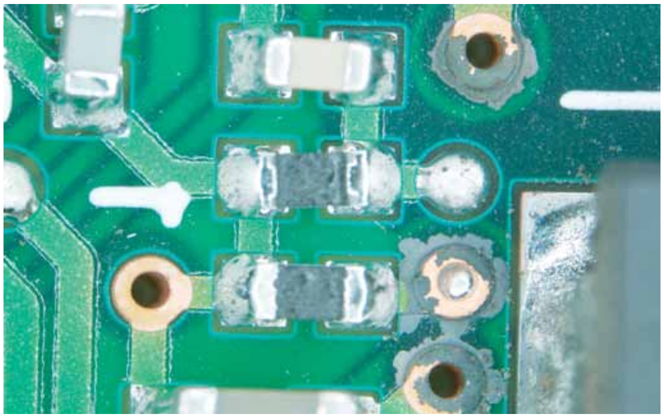

Figure 1: Sulfur-bearing gas corrosive attack of copper on a RoHS-compliant circuit board protected by OSP finish.

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 recent publications on the subject (Reid et al. 2007; Cullen and O'Brien 2004; Veale 2005; Sahu 2007; Scheller 2007; Hillman et al. 2007; Xu et al. 2007; Mazurkiewicz 2006), led to the need for the ASHRAE white paper on gaseous and particulate contamination limits in data centers that recommends that in addition to temper ature and humidity, dust and gaseous contamination should also be monitored and controlled (ASHRAE 2009a). These additional environmental measures 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:

1. Recent papers have reported copper creep corrosion on circuit boards (Cullen and O'Brien 2004; Mazurkiewicz 2006; Mukadam et al. 2006; Scheller 2007; Xu det al. 2007). The two common circuit board types suffering from copper creep corrosion are immersion silver (ImAg) and organic solder-ability preservative (OSP) technologies. The sulfide-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*.

2. 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 that undermine the integrity of the package. The package with its integrity breeched exposes the underlying silver 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 as needles or nodules, under a low power microscope, as shown in *Figure 2*.

The reduction of circuit board feature sizes and the miniaturization of components, which is necessary in order to improve hardware performance, make the hardware more prone to attack by corrosive particles and gases. 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 higher risk of failure. Therefore, the need to control data center airborne contaminants and to specify their recommended 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: These 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: Dust settled on printed circuit boards can lead to component corrosion and/or to the electrical short circuiting of closely spaced features.
- Electrical effects: These effects include impedance changes and electronic circuit conductor bridging.

Dust is ubiquitous. Even with our best filtration efforts, dust will be present in a data center and will settle on electronic

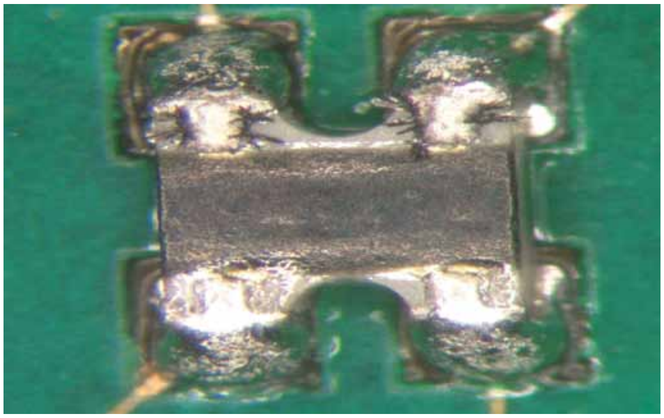

Figure 2: Sulfur-bearing gas corrosive attack of silver termination in a surface mount resistor showing black silver sulfide needles (circled) growing out of the resistor

Table 1: Gaseous Corrosivity Levels per ANSI/ISA-71.04-1985

Severity level	Copper reactivity level	Description
G1 Mild	30 nm/month	An environment sufficiently well-controlled such that corrosion is not a factor in determining equipment reliability.
G2 Moderate	30-100 nm/month	An environment in which the effects of corrosion are measurable and may be a factor in determining equipment reliability.
G3 Harsh	100-200 nm/month	An environment in which there is high probability that corrosive attack will occur.
GX Severe	>200 nm/month	An environment in which only specially designed and packaged equipment would be expected to survive.

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 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 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 datacenters. Sea salt can be carried 10km (6m) inland or farther by high winds present in coastal areas and can damage electronic devices at this range (Bennett et al. 1969; Crossland and Wright 1973).

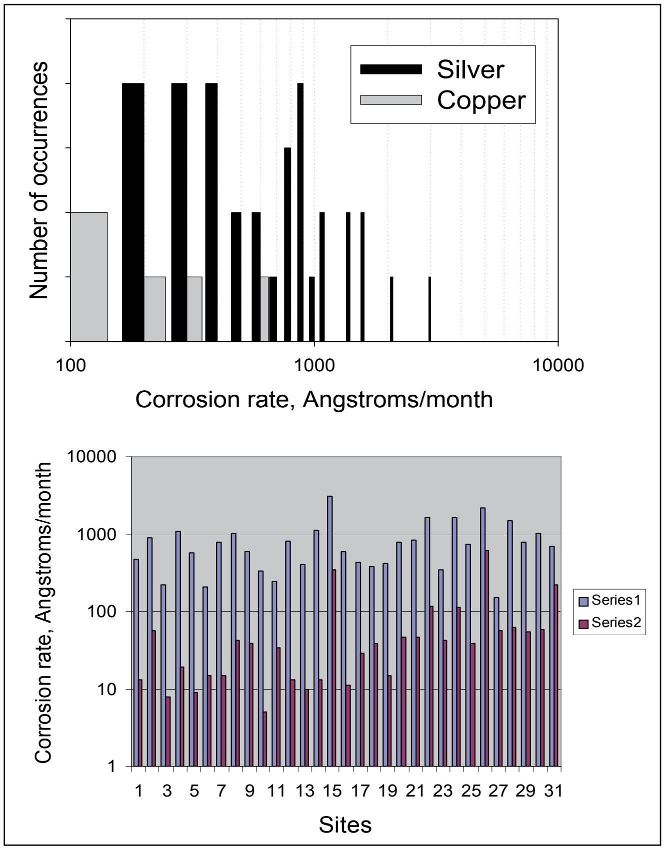

Figure 3: Measured copper creep corrosion and/or silver corrosion rates in data centers that reported IT hardware fails. The copper corrosion rate average and standard deviation was 7.1 and 12.1 nm/month. . The silver corrosion rate average and standard deviation was 84.8 and 64.1 nm/month. Series 1 refers to silver corrosion and series 2 to copper. Notice that in these 31 sites with known hardware failures due to corrosion, the silver corrosion rate was typically an order of magnitude or more greater than the copper corrosion rate.

One mechanism by which dust degrades the reliability of printed circuit boards involves the absorption of moisture by the settled dust from the environment. The ionic contamination in the dust degrades the surface insulation resistance of the printed circuit board and in the worst case scenario leads to electrical shorting of closely spaced features via ion migration.

Deliquescent relative humidity, the relative humidity at which the dust absorbs enough moisture 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, degrading hardware reliability. A 1993 study by Comizzoli et al. showed that leakage current due to dust, from various locations worldwide, 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.

Under rare circumstances, harmful dust can also be generated within a data center. Humidifiers that depend on airborne water droplets evaporating to increase the humidity in the room may

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cause 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 a serious corrosion and ion migration threat. These humidifier-related corrosion problems can be mitigated by treating the humidifier water using reverse osmosis (ASHRAE 2009b).

In summary, most dust is benign. Corrosion and/or ion migration problems may arise under the rare circumstance 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 from corroding the hardware.

ISO 14644-1 (ISO 1999) has become the dominant, worldwide standard for classifying the cleanliness of air in terms of concentration of airborne particles. Data centers must be kept clean to ISO Class 8 with the strictness of the 95% upper confidence limit (Ortiz 2006). ISO Class 8 can be achieved 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 the data center may be filtered with MERV 11-13 filters as recommended by ASHRAE (ASHRAE 2009b).

Gaseous Contamination

Sulfur-bearing gases, such as sulfur dioxide (SO_2) and hydrogen sulfide (H_2S), are the most common gases in data centers causing hardware failures. An example of corrosion on a circuit board that was compliant with the Restriction of Hazardous Substances Directive (RoHS) (EU 2003) is shown in *Figure 1*.

Gaseous composition environmental limits have been published in ANSI/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 hardware failure rates for several reasons. First, gaseous composition determination is not a trivial task. Second, it is generally not a straight forward 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 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 corrosion rate of copper is a strong function of relative humidity, while the corrosion rate of silver has no dependence on humidity (Rice et al. 1981).

A very convenient and quantitative way to determine the gaseous corrosivity of a data center environment is the so called "reactive monitoring" method described in ANSI/ISA-71.04 (ISA1985). 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 1*. But the use of copper coupon alone has two major limitations: one is that copper is not sensitive to chlorine (Muller et al. 1991), a particularly corrosive contaminant to many metals, and the other is that copper corrosion is overly sensitive to relative humidity (Rice et al. 1981). The inclusion of a silver coupon helps differentiate the corrosivity contributions of gaseous contamination 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.

At present the ANSI/ISA-71.04 (ISA 1985) standard applies only to copper corrosion, but as already explained it is desired that copper and silver coupons be used together to classify data center corrosivity. In other words, for a data center to be classified as severity level G1, the copper and silver corrosion rates limits should not exceed 30nm/month. An unpublished copper and silver corrosion rate survey of data centers with hardware failures from copper creep corrosion and/or silver corrosion is plotted in *Figure 3* (Singh et al. 2009). Only a small fraction of these problem data centers had copper corrosion rates greater than 10nm/month and a vast majority of these problem data centers had silver corrosion rates greater than 30nm/month. Notice that in these 31 sites, the silver corrosion rate was typically an order of magnitude greater than the copper corrosion rate. This survey, which is limited to data centers with reported hardware failures, clearly indicates that copper corrosion rate is not a good indicator of the potential of hardware failures. To improve the prediction of corrosion-related failures based on copper and silver corrosion rates, a random survey of data centers, with and without corrosion-related failures, is needed.

The ANSI/ISA-71.04-1985 is a well established, widely accepted standard that states that severity level G1 has copper corrosion rate less than 30nm/month corresponding to a "mild environment sufficiently well-controlled such that corrosion is not a factor in determining equipment reliability" (ISA 1985, p. 13). While many agree that this level of copper corrosion may be too high for reliable operation of electronic hardware, more work needs to be done to justify lowering the acceptable copper and silver corrosion rates. In the meantime, a maximum corrosion rate of 30nm/month for both copper and silver should be the

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acceptable gaseous corrosivity limits for data centers.

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 5cm (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 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 to be exposed for one month to get a good measure of the corrosivity of the environment. For data centers with air-side economizers, it is necessary to have real-time monitors that react quickly to events outside the data centers that may release corrosive gases that may flow into the data centers. 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 highly sensitive quartz crystal microbalance. The other determines gaseous corrosivity by measuring the rate of increase of metal thin films. Changes in corrosive gas composition can be detected on a real-time basis that may allow preventive measures to be taken, such as shutting off outside air from entering the data center.

Summary of Recommended Particulate and Gaseous Contamination limits

Recommended operating and non-operating environment	
Gaseous contamination	Severity level G1 as per ANSI/ISA 71.04-19851 which states that the reactivity rate of copper coupons shall be less than 30 nm/month (0.0039 μg/cm^2-hour weight gain)2. In addition, the reactivity rate of silver coupons shall be less than 30 nm/month (0.0035 μg/cm^2-hour weight gain)3. The reactive monitoring of gaseous corrosivity should be conducted approximately 2 inches (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.
Particulate contamination	1. Data centers must meet the cleanliness level of ISO class 8. The deliquescent relative humidity of the particulate contamination should be more than 60%.

Notes

1. ANSI/ISA-71.04.1985. "Environmental conditions for process measurement and control systems: Airborne contaminants." Instrument Society of America, Research Triangle Park, NC, 1985.

2. The derivation of the equivalence between the rate of copper corrosion product thickness growth in nm/month and the rate of weight gain assumes that Cu_2S and Cu_2O grow in equal proportions.

3. The derivation of the equivalence between the rate of silver corrosion product thickness growth in nm/month and the rate of weight gain assumes that Ag_2S is the only corrosion product.

4. 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.

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