Gaseous and Particulate Contamination Guidelines for Data Centers

Whitepaper prepared by ASHRAE Technical Committee (TC) 9.9
Mission Critical Facilities, Technology Spaces, and Electronic Equipment

This ASHRAE white paper on data center airborne contamination was developed by members of the TC 9.9 committee representing the following IT equipment manufacturers: AMD, Cisco, Cray, Dell, EMC, Hitachi, HP, IBM, Intel, Seagate, SGI, and Sun.

Executive Summary

ASHRAE TC 9.9 committee recently published the 2008 ASHRAE Environmental Guidelines for Datacom Equipment which extended the temperature-humidity envelope to provide greater flexibility in data center facility operations, particularly with the goal of reducing energy consumption. The recommended temperature limits are from 18^{o}C (64.4°F) to 27^{o}C (80.6°F). The humidity is limited to less than 60% with the lower and upper dew point temperatures of 5.5^{o}C (41.9°F) and 15^{o}C (59°F).

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, led to the need for this white paper that recommends 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.

Effects of airborne contaminations on datacenter equipment can be broken into three main categories: Chemical effects, mechanical effects and electrical effects. Two common chemical failure modes are copper creep corrosion on circuit boards and the corrosion of silver metallization in miniature surface mounted components. Mechanical effects include heat sink fouling, optical signal interference, increased friction, etc. Electrical effects include changes in circuit impedance, arcing, etc. 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 contamination in the data center environment. Manufacturers are in a constant struggle to maintain the reliability of their hardware with ever shrinking feature sizes, without taking the added costly measure of hardening all their IT equipment, most of which is not installed in corrosive environments where it can be exposed to higher risk of failure.

Most data centers are well designed and are in areas with relatively clean environments and most contamination is benign. Most data centers should not experience particulate or gaseous contamination related hardware failures. This paper is primarily targeted at a minority of data centers which may have harmful environments arising from the ingress of outdoor particulate and/or gaseous contamination. In some rare instances, contamination has been known to be generated within the data center.

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

1. The room air may be continuously filtered with MERV 8 filters as recommended by ANSI/ASHRAE Standard 127-2007, Method of Testing for Rating Computer and Data Processing Room Unitary Air Conditioners.
2. Air entering a data center may be filtered with MERV 11 or MERV 13 filters as recommended by ASHRAE book titled, “Particulate and Gaseous Contamination in Datacom Environments”.

Sources of dust inside data centers should be reduced. The gaseous contamination should be within the modified ANSI/ISA-71.04-1985 severity level G1 that meets:

1. A copper reactivity rate of less than 300Å/month, and
2. A silver reactivity rate of less than 300Å/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.

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 them. The net effect is the miniaturizing of all electronic components and their ever increasing packaging density which have 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 approach the size 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 2007; Cullen 2004; Veale; Sahu 2007; Schueller 2007; Hillman; Xu ; Mazurkiewicz 2006), led to the need for this white paper that recommends that in addition to temperature-humidity control, dust and gaseous contamination should also be monitored and controlled. 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 2004; Mazurkiewicz 2006; Mukadam 2006; Scheller 2007; Xu 2007). The two common circuit board types suffering from copper creep corrosion are immersion silver (ImAg) and organic solderability 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.
2. Some recent papers have reported corrosion of miniature surface mounted components that contain silver (Hillman; Reid 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 1.

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

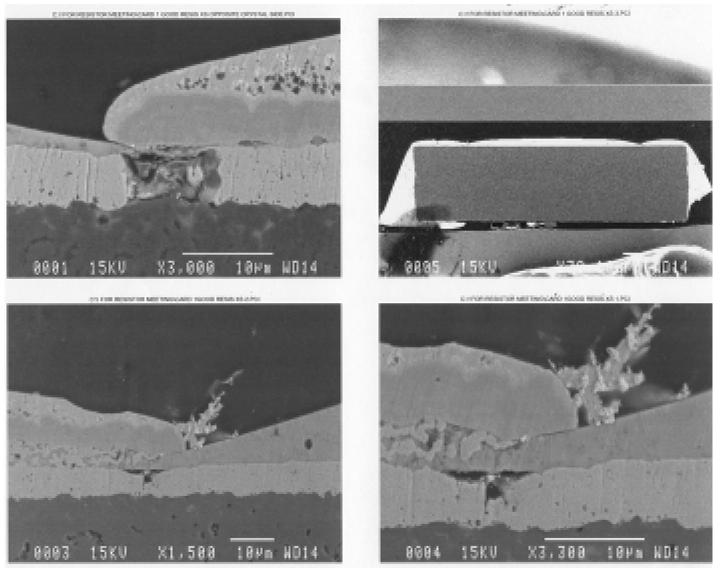


Figure 1: Example of a component failure due to an environment high in sulfur-bearing gases attacking the silver metallization in the component producing silver sulfide "flowers."

Airborne dust

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

- 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 hardware. Fortunately, most dust is benign. Only under rare circumstance 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 1993). The coarse dust particles have mineral and biological origin formed mostly by wind-induced abrasion and can remain airborne for a few days. The 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 10km (6 miles) inland or farther by high winds present in coastal areas and can damage electronic devices at this range (Bennett 1969; Crossland 1973).

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 wet dust degrades the surface insulation resistance of the printed circuit board and in the worst-case scenario leads to the electrical short circuiting of closely spaced features via ion migration. Figure 2 is 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, degrading hardware reliability. A 1993

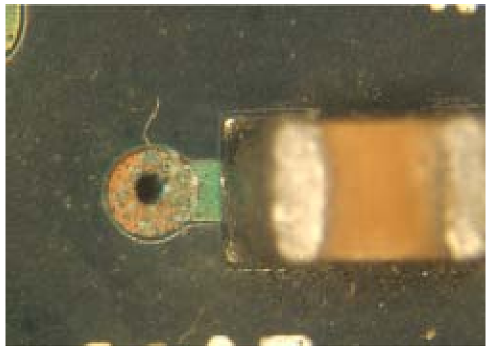


Figure 2: Corrosion of a plated through hole because of wetted ionic dust high in magnesium chloride.

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 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 2009a).

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

In summary, most dust in 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 the data center must be kept below 60% to avoid any dust from corroding the hardware.

Another form of particulate contamination very harmful to hardware reliability is the 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 2004; Lahtinen 2008).

Zinc whiskers, that may sometimes grow to be 1 to 2 mm long, 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 under-floor cables. If zinc whiskers are ingested by IT equipment, circuit with voltages higher than about 25V 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 dim 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 whisker presence. To confirm the presence of zinc whiskers, specimens should be collected using carbon adhesive tabs and viewed under a scanning electron microscope (SEM). 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. Table 1 below provides maximum concentration levels for each ISO class (ASHRAE 2009a).

Data centers must 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 may be achieved simply by specifying the following means of filtration:

1. The room air may be continuously filtered with MERV 8 filters as recommended by ANSI/ASHRAE Standard 127-2007, Method of Testing for Rating Computer and Data Processing room Unitary Air Conditioners.
2. Air entering a data center may be filtered with MERV 11 or MERV 13 filters as recommended by ASHRAE Book titled "Particulate and Gaseous Contamination in Datacom Environments." (ASHRAE 2009a)

For data centers with airside economizers, the choice of filters to achieve ISO class 8 cleanliness depends on the specific conditions present at that data center.

Table 1: *ISO 14644-1 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					
	> 0.1 µm	**> 0.2 µm**	**> 0.3 µm**	**> 0.5 µm**	**> 1 µm**	**> 5 µm**
Class 1	10	2				
Class 2	100	24	10	4		
Class 3	1000	237	102	35	8	
Class 4	10,000	2,370	1,020	352	83	
Class 5	100,000	23,700	10,200	3,520	832	29
Class 6	1,000,000	237,000	102,000	35,200	8,320	293
Class 7				352,000	83,200	2,930
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.						

Gaseous contamination

Sulfur-bearing gases, such as SO_2 and H_2S, are the most common gases in data centers causing hardware corrosion (Rice 1981). An example of corrosion on a RoHS-compliant circuit board due to gaseous contamination is shown in Figure 3.

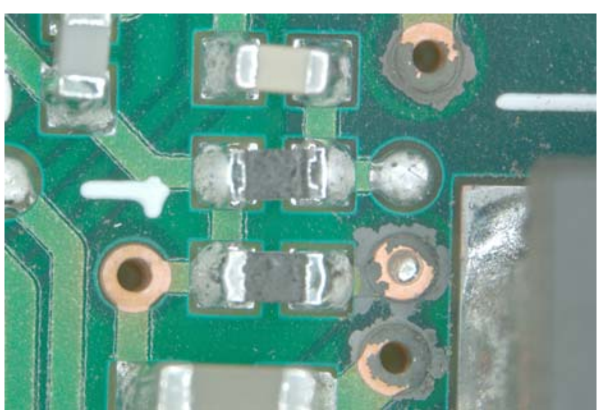


Figure 3: Sulfur-bearing gas corrosive attack of copper on a RoHS-compliant circuit board protected by OSP finish.

Gaseous composition environmental limits have been published in ANSI/ISA-71.04-1985. 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 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 sulfur dioxide or hydrogen sulfide alone are not very corrosive to silver or to copper but the combination of these gases with other gases such as nitrogen dioxide and/or ozone 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 1981).

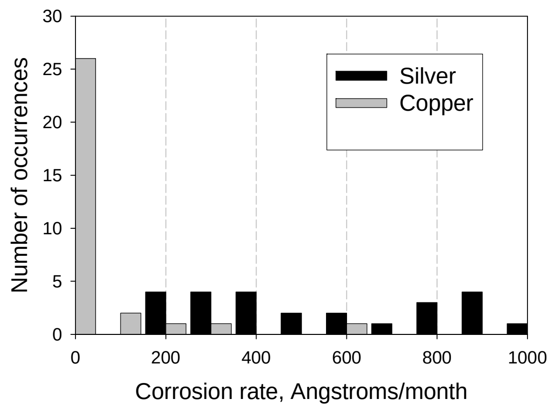
A very convenient and quantitative way to determine the gaseous corrosivity of a data center environment is the so called “reactive monitoring” method described in ANSI/ISA-71.04-1985. This method exposes a copper coupon to the environment for one month and analyzes the corrosion product thickness and chemistry using coulomeric reduction to classify the environment into one of four severity levels decribed in Table 2. But the use of copper coupon alone has two major limitations: One is that copper is not sensitive to chlorine, a particularly corrosive contaminant 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 corrosivity contribtions of gasous contamination and relative humidity. If it turns out that the relative humidity is playing a dominant role in the corrosion process, then the corrosivity can be decreased simply by lowering the relative humidity in the data center. It is now common practive to include silver coupons along with copper coupons to gain greater insight into the chemistry of the corrosive gases in the environment.

Table 2: *Gaseous Corrosivity Levels per ANSI/ISA-71.04-1985*

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

At present the ANSI/ISA-71.04-1985 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 300Å/month. A recent copper and silver corrosion rate survey, done by IBM, of data centers with hardware failures from copper creep corrosion and/or silver corrosion is plotted in Figure 4. Only a small fraction of these problem data centers had copper corrosion rates greater than 100Å/month; and all these problem data centers had silver corrosion rates greater than 100Å/month. Notice that in these 31 sites, the silver corrosion rate was typically an order of magnitude or more 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 300Å/month corresponding to a “mild environment sufficiently well-controlled such that corrosion is not a factor in determining equipment reliability.” While Figure 4 shows and 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 copper of 300Å/month and a maximum corrosion rate of silver of 300Å/month should be used as the acceptable gaseous corrosivity limit for data centers. The gaseous contamination levels in a data center are a function of location and time of year. The



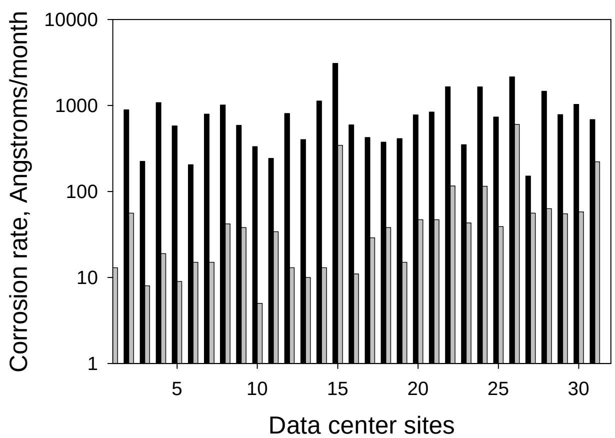


Figure 4: IT equipment fails in data centers with reported copper creep corrosion and/or silver corrosion. Not shown in the top chart are 6 occurrences of silver corrosion rate greater than 1000Å/month. It shows 26 occurrences of copper corrosion between 0-100Å/month and none for silver; 2 occurrences for copper and 4 for silver between 100-200Å/month; 2 occurrence for copper and 4 for silver between 200-300Å/month; and so on. Notice that, as shown in the bottom chart, 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.

location of interest for gaseous corrosivity monitoring is 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. 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 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 monitoring to react quickly to events outside the data centers that may release corrosive gases which 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 quartz crystal microbalance. The other determines gaseous corrosivity by measuring the rate of increase of resistance of metal thin films. Changes in gaseous corrosivity can be detected on a real-time basis that may allow preventive measures to be taken, such as shutting off outside corrosive air from entering the data center

Gas-phase filtration of air in data centers

For data centers that do not fall within the modified ANSI/ISA-71.04-1985 severity level G1 for copper and silver corrosion, gas-phase filtration is recommended. The air entering the data center should be gas-phase filtered to prevent gaseous contaminants from entering the data center. The blowers at the air inlet could be used to pressurize the data center to avoid contaminated outdoor air from leaking into the data center. The air in the data center should be re-circulated 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 ANSI/ISA-71.04-1985 severity level G1 for copper and silver corrosion.

2008 ASHRAE Environmental Guidelines for Datacom Equipment

To provide greater flexibility in facility operations, particularly with the goal of reduced energy consumption in data centers, ASHRAE TC 9.9 committee has revisited these recommended equipment environmental specifications, specifically the recommended envelope for classes 1 and 2. The recommended envelope is the same for both of these environmental classes. The result of this effort has been to expand the recommended operating environment envelope. The purpose of the recommended envelope is to give guidance to data center operators on maintaining high reliability and also operating their data centers in the most energy efficient manner. The allowable envelope is where IT manufacturers test their equipment in order to verify that the equipment will function within those environmental boundaries. Typically manufacturers will perform a number of tests prior to announcement of a product to verify that their product meets all the functionality requirements within this 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. 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 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 and 2008 recommended envelope data is shown in Table 3.

Table 3. *ASHRAE Recommended Environment for Temperature and Moisture (ASHRAE 2009b)*

	2004 Version	2008 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 dew point (41.9°F)
High End Moisture	55% relative humidity	60% relative humidity and 15°C dew point (59°F dew point)

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 details of the new guidelines are documented in the second edition of the Thermal Guideline book (Thermal Guidelines for Data Processing Environments, Second Edition, ASHRAE 2009b).

Summary of recommended acceptable environmental limits

The recommended temperature-humidity, dust and gaseous limits are summarized in the following table:

Table 4. *ASHRAE Recommended Environments*

<table>
<tr><th colspan="2">Recommended operating environment[1, 4]</th></tr>
<tr><td>Temperature</td><td>18°C (64.4 °F) to 27°C (80.6 °F)[4]</td></tr>
<tr><td>Low end moisture</td><td>5.5°C (41.9 °F) dew point</td></tr>
<tr><td>High end moisture</td><td>60% relative humidity or 15°C (59 °F) dew point</td></tr>
<tr><td>Gaseous contamination</td><td>Severity level G1 as per ANSI/ISA 71.04-1985[2] which states that the reactivity rate of copper coupons shall be less than 300Å/month (≡ 0.0039 μg/cm²-hour weight gain)[6]. In addition, the reactivity rate of silver coupons shall be less than 300Å/month days (≡ 0.0035 μg/cm²-hour weight gain)[7]. 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 or where the air velocity is much higher.</td></tr>
<tr><td>Particulate contamination</td><td>1. Data centers must meet the cleanliness level of ISO 14644-1 class 8.
a. For data center without airside economizer, the ISO 14644-1 class 8 cleanliness may be met simply by the choice of the following filtration:
i. The room air may be continuously filtered with MERV 8 filters.
ii. Air entering a data center may be filtered with MERV 11 or preferably MERV 13 filters.
b. For data centers with airside economizers, the choice of filters to achieve ISO class 8 cleanliness depends on the specific conditions present at that data center.
2. The deliquescent relative humidity of the particulate contamination should be more than 60% RH[3].
3. Data centers must be free of zinc whiskers[5].</td></tr>
<tr><th colspan="2">Recommended non-operating environment[4]</th></tr>
<tr><td>Temperature</td><td>5°C (41 °F) to 45°C (113 °F)</td></tr>
<tr><td>Relative humidity</td><td>8% to 80%</td></tr>
<tr><td>High end moisture</td><td>27°C (80.6 °F) dew point</td></tr>
<tr><td>Gaseous contamination</td><td>Severity level G1 as per ANSI/ISA 71.04-1985[2] which states that the reactivity rate of copper coupons shall be less than 300Å/month (≡ 0.0039 μg/cm²-hour weight gain)[6]. In addition, the reactivity rate of silver coupons shall be less than 300Å/month (≡ 0.0035 μg/cm²-hour weight gain)[7]. 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.</td></tr>
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2. The deliquescent relative humidity of the particulate contamination should be more than 60% RH[3].
3. Data centers must be free of zinc whiskers[5].</td></tr>
</table>

Notes:
1. Gaseous contamination is measured 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. Derate the maximum recommended ambient temperature by 1°C (1.8 °F) for every 300m (984ft) over 1800m (5906ft). 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. ANSI/ISA-71.04.1985. "Environmental conditions for process measurement and control systems: Airborne contaminants." Instrument Society of America, Research Triangle Park, NC, 1985.
3. 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.
4. The machine should be in an environment that satisfies the recommended operating environment specification for at least one day before it is powered on.
5. 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.
6. 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.
7. 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/cm^2.hour and Å/30days corrosion rates for copper and silver

Papers on atmospheric corrosion of metals often report corrosion rates in terms of rate of weight gain in μg/cm^2.hour. ANSI/ISA Standard 71.04-1985 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.

$$\text{Silver specimen weight gain of } 1\mu g \equiv \frac{2\times 107.9+32}{32}\ \mu\text{g of } Ag_2S$$
$$\equiv 7.74\times 10^{-6}\ \text{g of } Ag_2S$$
$$\equiv \frac{7.74\times 10^{-6}}{7.23}\ \text{cm}^3\ \text{of } Ag_2S$$
$$\equiv 1.07\times 10^{-6}\ \text{cm}^3\ \text{of } Ag_2S$$

$$1\ \mu\text{g/cm}^2\text{.hour} \equiv 1.07\times 10^{-6}\ \text{cm/hour}$$
$$\equiv 1.07\times 10^{-6}\times 10^{8}\ \text{A/hour}$$
$$\equiv 107\times 24\times 30\ \text{A/30 days}$$
$$\equiv 7.7\times 10^{4}\ \text{A/30 days}$$

If we assume that the silver corrosion product is mostly Ag_2S, then 300Å/month rate of corrosion product growth is equivalent to 0.0039 μg/cm^2.hour 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.

$$\text{copper specimen weight gain of } 1\mu g \equiv \frac{2\times 63.55+32}{32}\ \mu\text{g of } Cu_2S$$
$$\equiv 5\times 10^{-6}\ \text{g of } Cu_2S$$
$$\equiv \frac{5\times 10^{-6}}{5.6}\ \text{cm}^3\ \text{of } Cu_2S$$
$$\equiv 0.9\times 10^{-6}\ \text{cm}^3\ \text{of } Cu_2S$$

$$1\ \mu\text{g/cm}^2\text{.hour} \equiv 0.9\times 10^{-6}\ \text{cm/hour}$$
$$\equiv 0.9\times 10^{-6}\times 10^{8}\ \text{A/hour}$$
$$\equiv 90\times 24\times 30\ \text{A/30 days}$$
$$\equiv 6.4\times 10^{4}\ \text{A/30 days}$$

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.

$$\text{copper specimen weight gain of } 1\mu g \equiv \frac{2\times 63.55+16}{16}\ \mu\text{g of Cu}_2\text{O}$$
$$\equiv 8.94\times 10^{-6}\ \text{g of Cu}_2\text{O}$$
$$\equiv \frac{8.94\times 10^{-6}}{6}\ \text{cm}^3\ \text{of Cu}_2\text{O}$$
$$\equiv 1.5\times 10^{-6}\ \text{cm}^3\ \text{of Cu}_2\text{O}$$

$$1\ \mu\text{g/cm}^2\text{.hour} \equiv 1.5\times 10^{-6}\ \text{cm/hour}$$
$$\equiv 1.5\times 10^{-6}\times 10^{8}\ \text{A/hour}$$
$$\equiv 1.5\times 10^{2}\times 24\times 30\ \text{A/30 days}$$
$$\equiv 10.8\times 10^{4}\ \text{A/30 days}$$

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

$$1\ \mu\text{g/cm}^2\text{.hour} \equiv 8.6\times 10^{4}\ \text{A/30 days}$$

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