

What's Creeping Around in Your Data Center?

ABSTRACT

*The European Union (EU) directive 2002/95/EC “on the **R**estriction of the use of certain **H**azardous Substances in electrical and electronic equipment” or **RoHS** was implemented in July 2006. However, this was only the first of many RoHS(-like) regulations that have been passed or are being considered in many countries. The aim being shared by almost all RoHS legislation is the elimination of lead in electronic products. These policies are now generally referred to as the RoHS Directive and are often referred to as “Lead-Free” legislation.*

A printed circuit board, or PCB, is used to mechanically support and electrically connect electronic components using conductive pathways laminated onto a non-conductive substrate. PCBs have conducting layers on their surface typically made of thin copper foil which if left unprotected, will oxidize and deteriorate. Research has shown that printed circuit boards made using lead-free materials can be more susceptible to corrosion than their tin/lead counterparts and it was soon discovered that lead-free products with immersion silver (ImmAg) surface finish will creep corrode in high sulfur environments. The majority of creep corrosion failures occurred on hard disk drives (HDD), graphic cards, and motherboards in desktop or workstation systems (only those with ImmAg PCB finish were affected).

Corrosion-induced failures are frequent in electronics products used in industrial environments. Now even in environments previously considered relatively benign with regards to electronics corrosion are experiencing serious problems as a direct result of RoHS compliance. Data centers in many urban locations have reported failures of servers and hard disk drives due to sulfur corrosion. Gaseous contamination can result in intermittent equipment glitches, unplanned shutdowns, or failure of critical systems that often result in significant business and financial loss.

Desktop and laptop computers, servers, data communications (datacom) equipment and other information technology (IT) equipment are now at risk due to RoHS. There are indications that this may even trickle down into personal computers and electronic devices.

Manufacturers have to comply with RoHS if they want to continue in to do business in the EU, China, etc., and many have taken the ImmAg route as their path to compliance. This has taken care of one issue but has presented new challenges with regards to equipment reliability.

INTRODUCTION

In 1998, the European Union (EU) discovered that alarmingly large amounts of hazardous waste were being dumped into landfill sites. Trends also indicated that the volumes were likely to grow 3-5 times faster than average municipal waste. This highlighted a massive, and growing, source of environmental contamination.

In order to address these issues, the member states of the EU decided to create the Waste Electrical and Electronics Equipment (WEEE, 2002/96/EC) directive, whose purpose was to:

1. Improve manufacturers' designs to reduce the creation of waste,
2. Make manufacturers responsible for certain phases of waste management,
3. Separate collections of electronic waste (from other types of waste), and
4. Create systems to improve treatment, refuse, and recycling of WEEE.

The WEEE directive laid the groundwork for additional legislation and a proposal called EEE (Environment of Electrical & Electronics Equipment) was also introduced along the same lines. However, this policy is generally referred to as the RoHS Directive and is often referred to as “Lead-Free” legislation. This is not a very accurate nickname, because it extends to other pollutants as well.

The European Union (EU) directive 2002/95/EC “on the **R**estriction of the use of certain **H**azardous Substances in electrical and electronic equipment” or **RoHS** was implemented in July 2006. This directive

applies to electrical and electronic equipment designed for use with a voltage rating not exceeding 1,000 volts for alternating current and 1,500 volts for direct current. The requirements of this directive are applicable to the member states of the European Union.

The purpose of the directive is to restrict the use of hazardous substances in electrical and electronic equipment and to contribute to the protection of human health and the environmentally sound recovery and disposal of waste electrical and electronic equipment. The EU's RoHS Directive restricts the use of six substances in electrical and electronic equipment: mercury (Hg), lead (Pb), hexavalent chromium (Cr(VI)), cadmium (Cd), polybrominated biphenyls (PBB) and polybrominated diphenyl ethers (PBDE).

In order to comply with the EU RoHS legislation, all of these substances must either be removed, or must be reduced to within maximum permitted concentrations, in any products containing electrical or electronic components that will be sold within the European Union. Manufacturers have made significant investments in new processes that will eliminate these substances – especially lead.

All applicable products in the EU market must now pass RoHS compliance. In short, RoHS impacts the entire electronics industry and compliance violations are costly – product quarantine, transport, rework, scrap, lost sales and man-hours, legal action, etc. Non-compliance also reflects poorly on brand and image and undercuts ongoing environmental and “due diligence” activities.

WHERE IS ROHS IN EFFECT?

Companies selling a broad range of electrical goods in the EU must now conform to WEEE and those same companies must also conform to RoHS. WEEE and RoHS rules, while laid down at the European level, are put into law at the national level. When exporting to Europe, it is essential to comply with national law in each relevant country. The EU law simply serves as a template for national laws, which may differ considerably. European countries currently requiring conformance with the EU RoHS Directive include: Austria, Belgium, Bulgaria, Croatia, Cyprus, Czech Republic, Denmark, Estonia, Finland, France, Germany, Greece, Hungary, Ireland, Italy, Latvia, Lithuania, Luxembourg, Malta, Netherlands, Norway, Poland, Portugal, Romania, Slovak Republic, Slovenia, Spain, Sweden, Switzerland, Turkey, and the United Kingdom.*

China RoHS regulations have also been put into effect and many consider them to be considerably more restrictive. As described by a potentially-impacted customer: “Without exemptions, it is impossible to build a compliant board” (Anon 2008)

RoHS regulations are also either in effect or pending in many countries – including the United States. Additional RoHS-like regulations include:

- Argentina has both a WEEE and RoHS bill.
- Japan recently adopted “RoHS” labeling requirements for certain products.
- Taiwan has a voluntary RoHS program.
- Korea is considering RoHS legislation.
- Australia is conducting a survey.

U.S. State bills:

- California SB20 – has the same requirements as EU RoHS except that its scope includes only products with displays larger than 4”.
- California AB2202 – includes all EU RoHS products.
- Minnesota – patterned after EU RoHS, however only for consumer products.
- Several other states are looking at RoHS legislation (see Figure 1).

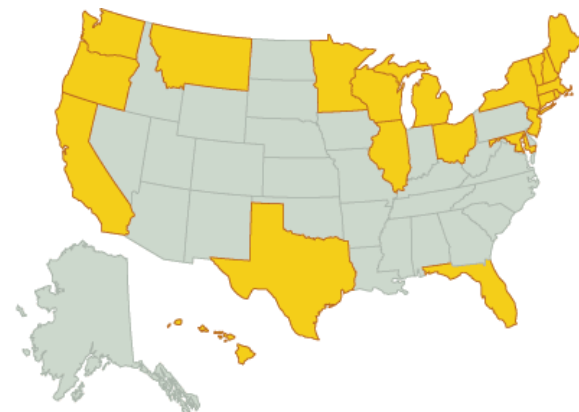


Figure 1. Yellow areas denote active or pending RoHS legislation (Anon A 2008)

* Note that Croatia, Norway, and Switzerland are not part of the EU. They may nevertheless have legislation implementing EU WEEE and RoHS rules, or similar legislation.

UNINTENDED CONSEQUENCES

An aim shared by almost all RoHS legislation is the elimination of lead in electronic products. Thus the main issue for the electronics industry became the use of lead in the manufacture of components and circuit board assemblies.

A printed circuit board, or PCB, is used to mechanically support and electrically connect electronic components using conductive pathways, or traces, laminated onto a non-conductive substrate. Alternative names are printed wiring board (PWB), and etched wiring board. A PCB populated with electronic components is a printed circuit assembly (PCA), also known as a printed circuit board assembly (PCBA).

All PCBs have conducting layers on their surface typically made of thin copper foil. If the copper is left unprotected, it will oxidize and deteriorate. Traditionally, any exposed copper was plated with lead(-based) solder by the hot air solder leveling (HASL) process.

HASL has been working well for many years, is the predominant surface finish used in the industry, and is also the cheapest PCB available. Now RoHS essentially makes PCBs using the HASL process obsolete. Failure modes on other common lead-free PCB finishes such as organic solder preservative (OSP) and electroless-nickel immersion gold (ENIG) make these technologies undesirable. As a result, alternatives such as immersion silver (ImmAg) and organically coated copper (OCC) are currently used as board finishes. Due to inherent processing difficulties with OCC boards, ImmAg boards are quickly becoming the standard PCB finish in the electronics industry (Mazurkiewicz 2006).

Immersion silver would seem to have a bright future under RoHS (Anon B 2008). It is easy to apply to the boards, relatively inexpensive, and usually performs well. While ENIG presently has a larger market share, over the past 12 months more immersion silver process lines have been installed in PCB facilities than any other finish. However, some manufacturers have complained about issues with corrosion. If severe enough, this could lead to shorts and ultimate failure of the board.

The International Society for Automation (ISA)[†] Standard ISA-71.04-1985 (ISA 1985) classifies several levels of environmental severity for electrical and electronic systems: G1, G2, G3 and GX, providing a measure of the corrosion potential of an environment. G1 is benign and GX is open-ended and the most severe.

In a study performed by Rockwell Automation (Anon C 2008) looking at lead-free finishes, four alternate PCB finishes were subjected to an accelerated mixed flowing gas corrosion test. Important findings can be summarized as follows:

1. The immersion gold (ENIG) and immersion silver (ImmAg) surface finishes failed early in the testing. These coatings are the most susceptible to corrosion failures and are expected to be much more susceptible than traditional HASL coatings. The use of these two coatings may make the PCB the weak link with regard to the sensitivities of the electronic devices to corrosion.
2. None of the coatings can be considered immune from failure in an ISA Class G3 environment.
3. The gold and silver coatings could not be expected to survive a mid to high Class G2 environment based on these test results.

A leading world authority on RoHS, ERA Technology, has also reported that, “Recent research has shown that printed circuit boards made using lead-free materials can be more susceptible to corrosion than their tin/lead counterparts” (Anon D 2008). Industry is working diligently to address these concerns but they cannot be addressed overnight.

The Reliability and Failure Analysis group at ERA Technology has diagnosed failures in electronic devices due to interaction with low levels of gaseous sulfides – failures that caused both a financial impact to the manufacturers and safety issues with their customers. Recent work showed that corrosion could occur even with measured hydrogen sulfide levels as low as $0.2\mu\text{g}/\text{m}^3$ (0.14 ppb). Another reference describes the formation of a 200 angstrom (20 nanometers) thick layer of silver sulfide in 100 hours at a concentration of just $100\mu\text{g}/\text{m}^3$ [72 ppb] (Anon E 2008).

[†] Known as the Instrumentation Society of America when the standard was published and later as the Instrumentation, Systems, and Automation Society.

CAUSES OF CORROSION

Corrosion can be defined as “deterioration of a substance (usually a metal) because of a reaction with its environment” (ISA 1985). Corrosion of metals is actually a chemical reaction caused primarily by attack of gaseous contaminants and is accelerated by heat and moisture. Rapid shifts in either temperature or humidity cause small portions of circuits to fall below the dew point temperature, thereby facilitating condensation of contaminants. Note that even at low relative humidity (RH) corrosion may occur, depending on the temperature and contaminants present (Henriksen et al. 1991). Relative humidity above 50% accelerates corrosion by forming conductive solutions on a small scale on electronic components. Microscopic pools of condensation then absorb contaminant gases to become electrolytes where crystal growth and electroplating occur.

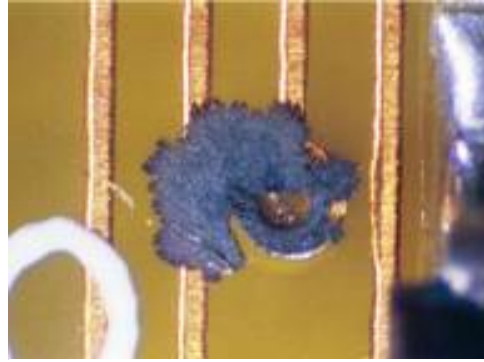


Figure 2. Short-circuit on PCB caused by corrosion.

These can cause breaks and shorts in the circuits by either coating a conductive surface with a non-conductive layer or by connecting conductive surfaces (Figure 2). Above 80% RH causes electronic corrosive damage regardless of the levels of contamination.

More generally, corrosive gases and water vapor coming into contact with a base metal result in the buildup of various chemical reaction products. As the chemical reactions continue, these corrosion products can form insulating layers on circuits which can lead to thermal failure, conductive failure, or short-circuits. Pitting and metal loss can also occur as a result of corrosive attack on metal. Pitting can be described as the formation of pits that penetrate into the metal causing structural damage and thus hindering edge connectors, etc. from completing the circuit. Metal loss is self-explanatory and would cause a conductive failure in the circuit.

Corrosive Gases (ISA 1985)

There are three types of gases that can be considered as prime candidates in the corrosion of data center electronics: acidic gases such as hydrogen sulfide, sulfur and nitrogen oxides, chlorine, and hydrogen fluoride; caustic gases, such as ammonia; and oxidizing gases, such as ozone. Of these, the acidic gases are of particular concern. For instance, it takes only 10 ppb of chlorine to inflict the same amount of damage as 25,000 ppb of ammonia.

Each site may have different combinations and concentration levels of corrosive gaseous contaminants. Performance degradation can occur rapidly or over many years, depending on the specific conditions at a site. Common sources of corrosive gases are shown in Table 1. Descriptions of common pollutants and a discussion of their contributions to equipment performance degradation follow.

Table 1. Sources of Reactive Environmental Contaminants (ISA 1985)			
Constituent	Symbol	Category	Common Sources
Acetic acid	CH ₃ COOH	Gas	Semiconductor manufacturing, wood and wood products, photo developing
Active organic nitrogen	N ₂	Gas	Automobile emissions, animal waste, vegetable combustion, sewage, wood pulping
Ammonia	NH ₃	Gas	Microbes, sewage, fertilizer manufacture, geothermal steam, refrigeration equipment, cleaning products, reproduction (blueprint) machines
Arsine	AsH ₃	Gas	Semiconductor manufacturing
Carbon	C	Solid	Incomplete combustion (aerosol constituent), foundry
Carbon monoxide	CO	Gas	Combustion, automobile emissions, microbes, trees, wood pulping
Chloride ions	Cl	Liquid	Aerosol content, oceanic processes, ore processing
Chlorine, Chlorine dioxide	Cl ₂ , ClO ₂	Gas	Chlorine manufacture, aluminum manufacture, paper mills, refuse decomposition, cleaning products
Ethylene	C ₂ H ₄	Gas	Fruit, vegetable, cut flower storage & transportation

Table 1. Sources of Reactive Environmental Contaminants (ISA 1985)			
Constituent	Symbol	Category	Common Sources
Formaldehyde	HCHO	Gas	Wood products, floor & wall coverings, adhesives, sealants, photo developing, tobacco smoke
Halogen compounds	HBr, HI	Gas	Automotive emissions
Hydrocarbons (alcohols, aldehydes, ketones, organic acids)	HC, THC	Gas	Automotive emissions, fossil fuel processing, tobacco smoke, water treatment, microbes. Many other sources, both natural and industrial, paper mills
Hydrogen chloride	HCl	Gas	Automobile emissions, combustion, oceanic processes, polymer combustion
Hydrogen fluoride	HF	Gas	Fertilizer manufacture, aluminum manufacture, ceramics manufacture, steel manufacture, electronic device manufacture, fossil fuel
Hydrogen sulfide	H ₂ S	Gas	Geothermal emissions, microbiological activities, fossil fuel processing, wood pulping, sewage treatment, combustion of fossil fuel, auto emissions, ore smelting, sulfuric acid manufacture
Inorganic dust		Solid	Crystal rock, rock and ore processing, combustion, blowing sand and many industrial sources
Mercaptans	S ₈ , R-SH	Gas	Foundries, sulfur manufacture
Oxides of nitrogen	NO _x	Gas	Automobile emissions, fossil fuel combustion, microbes, chemical industry
Ozone	O ₃	Gas	Atmospheric photochemical processes mainly involving nitrogen oxides and oxygenated hydrocarbons, automotive emissions, electrostatic filters
Sulfur dioxide	SO ₂ , SO ₃	Gas	Combustion of fossil fuel, auto emissions, ore smelting, sulfuric acid manufacture, tobacco smoke

Active sulfur compounds. Active sulfur compounds refers to hydrogen sulfide (H₂S), elemental sulfur (S), and organic sulfur compounds such as the mercaptans (R-SH). When present at low ppb levels, they rapidly attack copper, silver, aluminum, and iron alloys. The presence of moisture and small amounts of inorganic chlorine compounds and/or nitrogen oxides greatly accelerate sulfide corrosion. Note, however, that attack still occurs in low relative humidity environments. Active sulfurs rank with inorganic chlorides as the predominant cause of atmospheric corrosion.

Sulfur oxides. Oxidized forms of sulfur (SO₂, SO₃) are generated as combustion products of fossil fuels and from auto emissions. Low parts per billion levels of sulfur oxides can cause reactive metals to be less reactive and thus retard corrosion. At higher levels, however, they will attack certain types of metals. The reaction with metals normally occurs when these gases dissolve in water to form sulfurous and sulfuric acid (H₂SO₃ and H₂SO₄).

Nitrogen oxides (NO_x). Some common sources of reactive gas compounds (NO, NO₂, N₂O₄) are formed as combustion products of fossil fuels and have a critical role in the formation of ozone in the atmosphere. They are also believed to have a catalytic effect on corrosion of base metals by chlorides and sulfides. In the presence of moisture, some of these gases form nitric acid (HNO₃) that, in turn, attacks most common metals.

Inorganic chlorine compounds. This group includes chlorine (Cl₂), chlorine dioxide (ClO₂), hydrogen chloride (HCl), etc., and reactivity will depend upon the specific gas composition. In the presence of moisture, these gases generate chloride ions that, in turn, attack most copper, tin, silver, and iron alloys. These reactions are significant even when the gases are present at low ppb levels. At higher concentrations, many materials are oxidized by exposure to chlorinated gases. Particular care must be given to equipment that is exposed to atmospheres which contain chlorinated contaminants. Sources of chloride ions, such as bleaching operations, seawater, cooling tower vapors, and cleaning compounds, etc., should be considered when classifying industrial environments. They are seldom absent in major installations.

Hydrogen fluoride (HF). This compound is a member of the halogen family and reacts like inorganic chloride compounds.

Ammonia and derivatives. Reduced forms of nitrogen (ammonia, NH₃), amines, ammonium ions (NH₄⁺) occur mainly in fertilizer plants, agricultural applications, and chemical plants. Copper and copper alloys are particularly susceptible to corrosion in ammonia environments.

Photochemical species. The atmosphere contains a wide variety of unstable, reactive species that are formed by the reaction of sunlight with moisture and other atmospheric constituents. Some have lifetimes measured in fractions of a second as they participate in rapid chain reactions. In addition to ozone (O₃), a list of examples would include the hydroxyl radical as well as radicals of hydrocarbons, oxygenated hydrocarbons, nitrogen oxides, sulfur oxides, and water. Because of the transient nature of most of these species, their primary effect is on outdoor installations and enclosures. In general, metals are only slightly susceptible to photochemical effects. However, ozone can function as a catalyst in sulfide and chloride corrosion of metals.

Strong oxidants. This includes ozone plus certain chlorinated gases (chlorine, chlorine dioxide). Ozone is an unstable form of oxygen that is formed from diatomic oxygen by electrical discharge or by solar radiation in the atmosphere. These gases are powerful oxidizing agents. Photochemical oxidation - the combined effect of oxidants and ultraviolet light (sunlight) - is particularly potent.

Hydrogen sulfide (H₂S), sulfur dioxide (SO₂), and active chlorine compounds (Cl₂, HCl, ClO₂), have all been shown to cause significant corrosion in electrical and electronic equipment at concentrations of just a few parts per billion in air. Even at levels that are not noticed by or harmful to humans, these gases can be deadly to electronic equipment. Most of the odor threshold levels are much higher than the levels at which corrosive damage will occur.

THE NATURE OF CORROSION

When discussing electronic equipment, the corrosion of copper, silver, or composite materials gives the same result: a disruption of electrical current flow. The severity of the environment (i.e. the types and levels of gases, humidity, and temperature) will determine the speed at which corrosion forms and how soon corrosion-related effects may appear.

Sign of Corrosion

For the purposes of this paper, corrosion can be thought of as two distinct types: the first being the more conventional corrosive attack where the acid gases react with the metals themselves to form non-conductive salts and second type being “whisker growth”.

Creep corrosion. Any place where a non-precious metal meets the atmosphere, corrosion may occur. Some metals undergo self-limiting, or passive corrosion. Once an oxide or sulfide layer forms, it will not grow any further. The layer of corrosion products effectively insulates the underlying base metal from the environment, and further corrosion is prevented.

In active corrosion, the corrosion layer is not self-limiting. The base metal will continually corrode, and the corrosion product will tend to spread out from its point of origin. Any pre-plated or clad contact (coated before stamping) will have bare edges. These edges are free to corrode, and the corrosion product can grow from the edges and slowly spread across the surface as shown in Figure 3. This is known as “creep corrosion” (Anon F 2008).

Creep corrosion is a mass-transport process during which solid corrosion products migrate over a surface. Eventually, the corrosion product will interfere with the electrical connection by creating unacceptably high levels of contact resistance. Pollutants such as chlorine, hydrogen sulfide, and sulfur dioxide are known to promote creep corrosion. For components with noble metal pre-plated leadframes, creep corrosion is a potential reliability risk for long-term field applications (Zhao and Pecht 2005).

Pore Corrosion. In an ideal world, surface platings would be uniformly thick, continuous, and stress-free. In the real world, there will always be some imperfections in the plating. In many cases, platings will have pores, through which the base metal will be exposed. The degree of porosity depends on the plating thickness, application method, base metal roughness, and base metal cleanliness. As plating thickness increases, there is less likelihood of a pore extending all the way to the base metal. In a very thin plating layer (on the order of those used for gold), the likelihood is high that many pores will extend all the way through this layer. Platings over base metals with rough surfaces show more porosity than those over smooth surfaces. Dirt or oxide on the surface of the base metal can also lead to the appearance of pores.

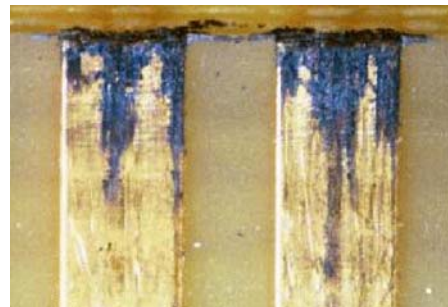


Figure 3. Example of creep corrosion on connectors

If the base metal is exposed to a corrosive environment through these pores, pore corrosion can occur. Base metal corrosion can occur entirely in the pores, where it may be hidden from view, or the corrosion product may creep across the surface (Anon F 2008). An example of this is shown in Figure 4. Pore corrosion is promoted by the many of the same gases that promote creep corrosion.

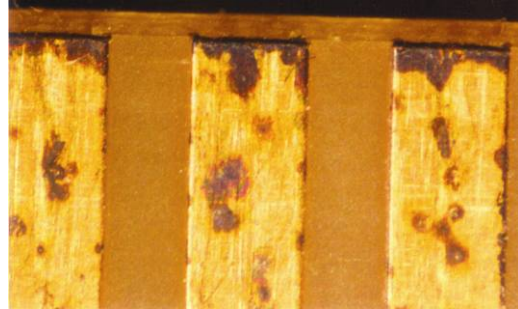


Figure 4. Example of pore corrosion on connectors

Via Corrosion. When a multi-layer circuit board is created, vertical interconnects must be added. These interconnects are called vias and can be defined as a plated-through hole used to connect two or more conductor layers of a multilayer board, in which there is no intention to insert a component lead or other reinforcing material.

There are areas on circuit boards that can contain exposed copper, such as the inside of via barrels. The purpose of surface finish (or coating) is to protect the copper beneath. If the coating is complete, corrosion would not take place as rapidly. An experimental investigation of the via holes on a typical silver immersion board shows that the silver coating does not typically extend all the way through the via barrel (Mazurkiewicz 2006).

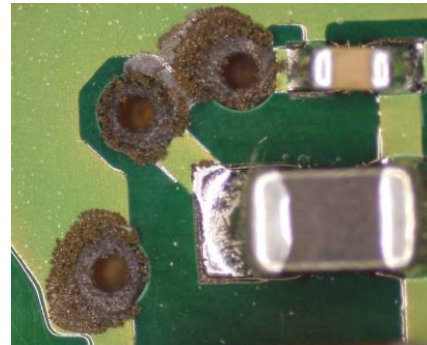


Figure 5. Example of via corrosion.

In situations where the via hole is not completely coated, copper metal is vulnerable to atmospheric attack (Figure 5). This situation which involves a more noble metal coating a metal that is prone to oxidation in the presence of an electrolyte (atmospheric water) is highly prone to galvanic corrosion. Indeed, this appears to be the case when one reviews the dozens of incidents and hundreds of failures in which PCB technology is used in an environment high in reduced sulfur gasses. The majority of the failures show the heaviest corrosion mainly inside the via holes.

Whisker Growth. This type of corrosion typically refers to electrically conductive, crystalline structures of tin that sometimes grow from surfaces where tin (especially electroplated tin) is used as a final finish. Tin whiskers have been observed to grow to lengths of several millimeters (mm) and in rare instances to lengths up to 10 mm. Numerous electronic system failures have been attributed to short circuits caused by tin whiskers that bridge closely-spaced circuit elements maintained at different electrical potentials (Anon G 2008).

“Whisker growth” can be described as corrosion in which microscopic metal crystals grow out of the surface of the conductive metal. It is caused by the presence of sulfide molecules, e.g., silver sulfide on a silver surface, which can migrate freely over the metallic surface and collect at dendrite boundaries where nucleation takes place and sulfide crystals grow out of the surface of the metal. These whiskers can be of size long enough to connect portions on a board, chip, etc. and cause short-circuits (Figure 6). By some accounts, whisker growth accounts for approximately 10% of documented failures (Brusse et al. 2007).

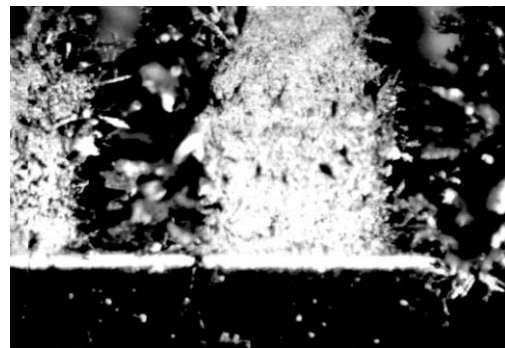


Figure 6. Tin whiskers causing bridging across circuits

Other specific areas on PCB that are particularly sensitive to corrosion attack are briefly described below.

Edge connectors. These contacts are typically gold-plated over a nickel-plated copper substrate that is intended to ensure that the electrical contact between the board and the connector is maintained with the highest integrity over a long period of time. Since the gold layer is typically only between 4 and 8 μm thick, and at these plating thicknesses fairly porous, the passage of corrosive gases can occur through the gold layer and attack the underlying layers of nickel and/or copper.

The salts formed by corrosion reactions are of a higher volume than the pure metal and can either “flake off” the gold plating or be forced back up through the pores onto the surface of the gold plating. In both cases the contact arm no longer rests on the conductive metal but rests on a high resistance coating.

Earlier generations of electronic equipment with operating voltages as high as 24-48 volts DC, equipment failures only occurred after many years of operation since these voltages were high enough to break down the thin high-resistance layers caused by salt formation. Modern electronics are, however, much more sensitive to this type of corrosion since operating voltages are lower and cannot break down these corrosion films.

Pin Connectors. The problems experienced on pin connectors and IC plug-in sockets show the same problems as edge connectors. However, edge connectors appear to be more susceptible to corrosive attack and failures occur earlier than on pin connectors and IC sockets.

Wire-wrap Connections. Wire-wrap connection pins are particularly sensitive to corrosive attack because the wire forms a “smear” contact between the pin and the wire with up to four different metallic alloys being exposed to the atmosphere. Corrosive attack can thus occur concurrently with electrolytic action which greatly increases the corrosive influence.

Electrical Systems. Previous generations of electronic equipment contained only heavy current systems in which the build-up of corrosion by-products could cause overheating that result in a reduction in equipment life. Today, however, central offices, internet data centers, and remote locations using the most advanced microelectronics operate with much lower voltages and are much more sensitive to corrosive attack as described above. As such, the air quality in these rooms will have a great effect on the life of the equipment.

MEASURING CORROSION

There are many methods available to measure ambient air quality and two methods have been used extensively for environmental characterization with regards to corrosion. One is a direct measure of selected gaseous air pollutants. The other, which can be termed “reactivity monitoring,” provides a quantitative measure of the overall corrosion potential of an environment.

Pollution analysis may provide short-term estimates for specific sites. High values will confirm that a severe environment exists. The reverse, however, is not necessarily true. Many environments may contain a complex mixture of contaminants that interact to greatly accelerate (or retard) the corrosive action of individual gas species.

As a direct measure of overall corrosion potential, reactivity monitoring involves the placement of specially prepared metal coupons in the operating environments.[‡] Analyses may consist of measurements of film thickness, film chemistry, or weight loss. However, ISA Standard 71.04-1985 references measurement of film thickness by cathodic (electrolytic, coulometric) reduction as a preferred method to perform reactivity monitoring. By using this method, the air with contaminant gases can be rated as to its effect on the electronic equipment.

Quantifying the Corrosive Potential of an Environment

Environmental Reactivity Coupons. Since the ISA Standard was published hundreds of thousands these “environmental reactivity coupons,” or ERCs, have been used to provide a measure of the corrosive potential of an environment (Figure 7). ERCs may be used to indicate the presence of SO₂, NO₂, Cl₂, O₃, and many other corrosive materials which can cause damage to PCBs and many types of electronic equipment.

ERCs originally used only copper reactivity to establish environmental classifications. However, copper is not sufficiently sensitive to many of those pollutants ubiquitous to most urban environments - the same environments in which most data centers are located. Further, copper coupons cannot detect the presence of

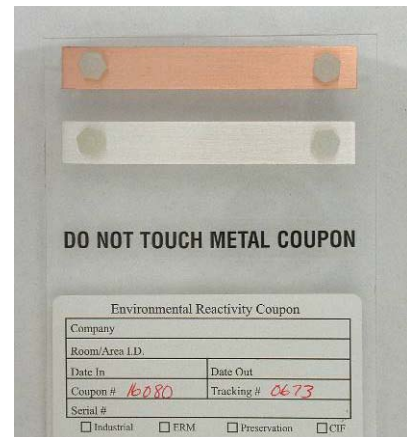


Figure 7. Copper / silver ERC.

[‡] Copper has been the primary coupon material because data exist which correlates copper film formation with reactive (corrosive) environments and it has proven to be particularly useful for environmental characterization.

chlorine, a particularly dangerous contaminant to metals. Finally, with the passage of RoHS legislation, and the switch to Imm-Ag and other lead-free finishes, many control systems manufacturers and end-users are now questioning whether this type of environmental monitoring is adequate or not.

Due to all of this, the use of silver reactivity monitoring, in addition to copper reactivity monitoring, has seen an increase in use in these environments. Although silver is not an equipment reliability determinant in the ISA standard, it has been long been included because of independent studies citing silver being able to detect changes in the levels of gaseous contaminants in the ambient environment as small as 1 ppb and differentiate between different classes of contaminants as well as being a better indicator of environmental chlorine than copper (Rice et al 1981, Muller 1999).

The use of these two types of coupons presented, on occasion, results that were quite surprising. Some environments that were non-corrosive to copper, and thus considered harmless to equipment (by the ISA standard), were extremely corrosive to silver. While this alone does not necessarily indicate an environment requiring direct control of contaminants, it does point out the potential for corrosion-related effects. Many in the process industries (e.g., pulp and paper, petrochemical) feel that using copper-only reactivity monitoring results can seriously understate the potential for equipment failure in these environments (Muller 1990).

The primary reasons for using both copper and silver reactivity monitoring to gauge data center air quality are:

1. Corrosion on silver is not humidity-dependent. In a temperature and humidity-controlled data center, any corrosion that forms on silver can be attributed solely to the presence of chemical contaminants. Copper corrosion is humidity dependent and can therefore be attenuated in these environments.
2. Silver can be used to positively indicate the presence of inorganic chlorine which is an extremely reactive contaminant. Environmental chlorine cannot be definitively determined from copper ERC analysis.
3. Silver is much more sensitive to low levels of contaminants. This is due to a passivating oxide layer that can form on copper. Silver is not reactive with oxygen and, again, any corrosion that forms is due to the presence of reactive contaminant gases.

The corrosion reported from reactivity monitoring with ERCs is actually the sum of individual corrosion films. For copper coupons, sulfide and oxide films are most commonly produced and are reported as copper sulfide (Cu_2S) and copper oxide (Cu_2O), respectively. For silver coupons, sulfide, chloride, and oxide films may be produced and are reported as silver sulfide (Ag_2S), silver chloride (AgCl), and silver oxide (Ag_2O), respectively. Each coupon is analyzed as to the type and amount of film present and its relative contribution to the total corrosion produced.

Environmental Reactivity Monitors. One consideration faced in designing an air quality monitoring program is the choice of passive vs. active sampling. The immediate feedback of an active monitor is a most desirable aspect and is what often precludes the use of passive monitors. The main limitation in the use of ERCs is their inability to provide a continuous environmental classification. To address this, reactivity monitoring has been taken a step farther through the development of a real-time monitoring device employing metal-plated quartz crystal microbalances (QCMs, Figure 8). These microprocessor-controlled devices are able to measure the total environmental corrosion attributable to gaseous pollutants. ERMs employing QCMs can detect and record changes <1 ppb for many common contaminants. This ability is regarded as one of the main requirements for any real-time monitoring protocol to be used in data center environments (England et al. 1991, Weiller 1994).

To date, there are two commercially available ERMs that employ copper and silver-plated QCMs that provide real-time information on the amount of corrosion forming due to the presence of gaseous contaminants. These devices measure film thickness similar to the ERCs and report cumulative and incremental corrosion rates in angstroms, correlating to the reporting requirements of ISA 71.04-1985.

One device measures corrosion on a continuous basis and allows for preventive action to be taken before serious damage has occurred. Appropriate reactivity and alarm levels for a particular application can

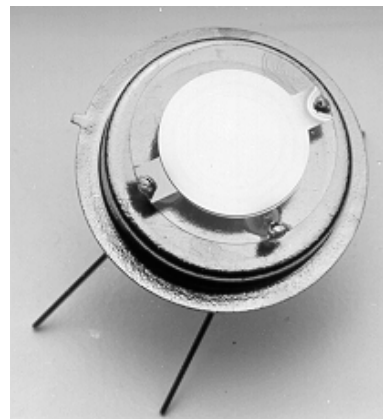


Figure 8. QCM

be adjusted. It can be operated independently as a battery-operated data logger unit or operated as a data transmitter wired directly into a facility monitoring system (FMS). Environmental classification databases can be established and maintained to provide historical data.

The second device is similar in that it employs QCMs to monitor the environment in real-time. However, it does not store data but transmits it directly to an FMS or computer directly via a 4-20 mA output signal.

Classification of Reactive Environments (ISA 1985)

The classification of reactive environments per ISA Standard 71.04 is based on the thickness of the reaction film(s) formed on the copper coupon when determined by cathodic reduction. The total film thickness is measured in angstroms (Å) normalized to a one month exposure and correlated to severity levels that predict effects of corrosion on electronic equipment reliability. This classification scheme also provided approximations of the concentrations of gases in the environment being analyzed. The classification of reactive environments is shown in Table 2 and described and illustrated below (Figure 9).

Table 2. ISA Classification of reactive environments						
Severity Level		G1	G2	G3	GX	
		Mild	Moderate	Harsh	Severe	
Copper Reactivity Level (in angstroms) [§]		< 300	< 1000	< 2000	≥2000	
The gas concentration levels shown below are provided for reference purposes. They are believed to approximate the Copper Reactivity Levels stated above, providing the relative humidity is less than 50%. For a given gas concentration, the Severity Level (and Copper Reactivity Level) can be expected to be increased by one level for each 10% increase in relative humidity above 50% or for a relative humidity rate of change greater than 6% per hour.						
Gas Concentrations (in ppb)						
	Contaminant	Gas	Concentration			
Reactive Species ^{**} , ^{††}	Group A	H ₂ S	< 3	< 10	< 50	50
		SO ₂ , SO ₃	< 10	< 100	< 300	300
		Cl ₂	< 1	< 2	< 10	10
		NO _x	< 50	< 125	< 1250	1250
	Group B	HF	< 1	< 2	< 10	10
		NH ₃	< 500	< 10,000	< 25,000	25,000
		O ₃	< 2	< 25	< 100	100

Severity Level G1 – Mild. An environment sufficiently well-controlled such that corrosion is not a factor in determining equipment reliability.

Severity Level G2 – Moderate. An environment in which the effects of corrosion are measurable and may be a factor in determining equipment reliability.

Severity Level G3 – Harsh. An environment in which there is a high probability that corrosive attack will occur. These harsh levels should prompt further evaluation resulting in environmental controls or specially designed and packaged equipment.

Severity Level GX – Severe. An environment in which only specially designed and packaged equipment would be expected to survive. Specifications for equipment in this class are a matter of negotiation between user and supplier.

This classification scheme allows for the evaluation of a subject environment with respect to its corrosion potential and ultimately the reliability of electronic equipment being used in the environment. From this a decision can be made as to whether or not action is needed to improve the environment for the protection of the electronic equipment.

[§] Measured in angstroms after one month's exposure.

^{**} The Group A contaminants often occur together and the reactivity levels include the synergistic effects of these contaminants.

^{††} The synergistic effects of Group B contaminants are not known at this time.

SO WHAT DOES ALL THIS MEAN?

Corrosion-induced failures are frequent in electronics products used in industrial environments. A typical failure mechanism of electronic systems in these environments is the reaction of atmospheric sulfur with exposed metals – particularly copper and silver. These metals are found in PCB traces, integrated circuit (IC) leads and device terminations. Copper sulfide or silver corrosion products can grow and creep across surfaces such as IC packages and PCB substrates.

Historically, the use of silver in electronic assemblies has been a reliability risk unless the silver is protected from the environment. Creep corrosion (electromigration) can occur quite readily in humid environments especially in the presence of small amounts of atmospheric sulfur and chlorides which are common in many industrial and other environments.

Manufacturers of industrial computer equipment specify the control of corrosive gases in their site planning guides and/or their terms and conditions to maintain warranties and service contracts. Now even environments previously considered benign with regards to electronics corrosion are experiencing serious problems as a direct result of RoHS compliance. Data centers in many urban locations have reported failures of servers and hard disk drives due to sulfur corrosion. There are hints that this may even trickle down into personal computers and electronic devices.

Many millions of lead-free desktop and notebook systems, and related peripherals, were put into service by Dell Computers starting in 2005, a year prior to the effective date of the RoHS legislation and a large amount of resources were invested in optimizing and qualifying lead-free assemblies. Field data showed the overall quality of Dell's lead-free products to be as good, and in some cases, better than the previous generation of tin-lead products (Schueller 2007).

However, one failure mechanism caused by the lead-free transition was not foreseen by Dell or the industry. It was soon discovered that lead-free products with ImmAg surface finish will creep corrode in high sulfur environments (ISA Class G2 or higher). The majority of creep corrosion failures occurred on hard disk drives (HDD), graphic cards, and motherboards in desktop or workstation systems (only those with ImmAg PCB finish were affected).

Echoing the study by Rockwell, Hewlett Packard (Mazurkiewicz 2006) documented several case studies where creep corrosion of ImmAg finish caused failures of computer systems in high sulfur environments. It was stated that sulfur-based corrosion failures increased dramatically upon introduction of ImmAg surface finish on computer products (due to ROHS requirements). Alcatel-Lucent also has experience with this issue in a paper detailing their work with mixed flowing gas testing of various lead-free surface finishes and their resistance to creep corrosion (Reid et al. 2007).

Analysis revealed the corrosion products to be copper sulfide (Cu_2S) and silver sulfide (Ag_2S). Other studies have shown that high amounts of Cu_2S typically indicate the presence of active sulfur compounds such as elemental sulfur, H_2S , or organic sulfur compounds. Ag_2S can also be formed by these contaminants but can also be formed by exposure to SO_2 contamination – a primary urban contaminant.

The most common failures are with the most common components, with the highest incidence of failures being found in capacitors, plastic encapsulated microcircuits (PEMs) and printed circuit boards (PCBs). A University of Maryland study of field failures from 70 companies revealed 30% of **ALL** failures were capacitors – mainly MLCCs [multilayer chip capacitors] (Anon H 2008).

CORROSION OF DATACOM EQUIPMENT

The reason for the dramatic increase in corrosion failures due to the use of ImmAg involves the propensity of silver and copper to react with sulfur. This is further complicated by the fact that there are areas on ImmAg circuit boards that contain both exposed silver and copper in contact, such as the inside of



Figure 9. QCMs and ERCs showing ISA classes G1-GX

via barrels. The purpose of the silver coating is to protect the copper beneath. If the coating was complete, corrosion would not take place as rapidly (Mazurkiewicz 2006).

ERCs and ERMs have been used to evaluate the severity levels of data center environments all over the world. It has been found that many areas have levels of corrosive contaminants high enough to be harmful to electronic equipment performance to the point of failure. Examples of reactivity monitoring data collected from data centers with documented cases of corrosion-related equipment failure (PCBs, servers, hard disk drives, etc.) is shown in Table 3 (Purafil 2008).

Type	Location	Copper Corrosion					Silver Corrosion			
		Cu ₂ S	Cu ₂ O	Cu-Unk	Total	ISA Level	AgCl	Ag ₂ S	Ag-Unk	Total
Bank	Inside DC	0	75	0	75	G1	0	636	0	636
FSC	Server Room	122	70	0	192	G1	0	524	0	524
TCC	Inside DC	162	105	0	267	G1	0	982	0	982
Bank	Inside DC	193	94	0	287	G1	0	785	0	785
Bank	DC supply air	0	288	0	288	G1	23	227	0	250
Bank	Under raised	258	89	0	347	G2	0	1,047	0	1,047
Bank	Data storage	265	91	0	356	G2	0	3,200	0	3,200
HQ	Inside DC	299	80	0	379	G2	0	1,603	0	1,603
Bank	Inside DC	334	75	0	409	G2	0	1,833	0	1,833
FSC	Inside DC	209	240	0	449	G2	0	106	0	106
FSC	Outside air	355	137	0	492	G2	135	353	0	488
Bank	DC supply air	426	85	0	511	G2	0	861	0	861
Bank	Inside DC	415	179	0	594	G2	0	1,122	0	1,122
TCC	Server room	474	143	0	617	G2	0	852	0	852
Bank	Under raised floor	587	180	0	767	G2	45	1,742	0	1,787
FSC	Hub room	1,702	320	0	2,022	GX	0	916	0	916
HQ	Outside air	620	1,549	0	2,169	GX	0	465	0	465
FSC	Hub room	1,595	686	0	2,281	GX	0	1,309	0	1,309
IC	Outside air	1,749	268	478	2,495	GX	835	96	96	1,027
Bank	Outside air	0	258	2,315	2,573	GX	87	552	0	639
FSC	Hub room	3,297	778	0	4,075	GX	0	1,440	0	1,440
HQ	Outside air	6,855	6,794	0	13,649	GX	0	5,044	2,421	7,465
HQ	Outside air	10,357	7,434	0	17,792	GX	0	1,651	2,631	4,282
TCC	Inside DC	20,000	0	0	20,000	GX	0	655	0	655
ISP	Server room	20,000	0	0	20,000	GX	0	810	0	810
Bank	Outside air	20,000	0	0	20,000	GX	387	374	715	1,476
Bank	Outside air	20,000	0	0	20,000	GX	0	2,855	0	2,855
FSC	Hub room	20,000	0	0	20,000	GX	0	3,404	0	3,404
FSC	Hub room	20,000	0	0	20,000	GX	0	3,535	0	3,535
FSC	Hub room	20,000	0	0	20,000	GX	0	3,927	0	3,927
ISP	Hub room	20,000	0	0	20,000	GX	0	4,114	0	4,114

Key: FSC = financial services company, HQ = company headquarters, IC = investment company, ISP = internet service provider, TCC = telephone call center

When interpreting the analysis results for the individual corrosion films, the detection of a silver sulfide (Ag₂S) film without a corresponding copper sulfide (Cu₂S) film usually indicates the presence of oxidized forms of sulfur such as SO₂ and SO₃. When both films are detected - as is the case here - it more often than not indicates the presence of active sulfur compounds such as elemental sulfur, H₂S, and organic sulfur compounds (e.g., mercaptans) as well. When both films are present and the amount of Cu₂S is

greater than 50% of the total corrosion, this is further evidence of the presence of active sulfur compounds in the subject environment.

Silver chloride (AgCl) indicates the presence of (an) inorganic chlorine compound(s), e.g., Cl₂, ClO₂, HCl.

The highlighted values in Table 3 under the Cu₂S and AgCl columns indicate an increased risk for corrosive attack regardless of the ISA Severity Level indicated. The shaded rows are locations where computer equipment would not be expected to survive without some type of additional environmental control, i.e., air cleaning to remove corrosive gases.

WHERE DO WE GO FROM HERE?

The requirement for corrosion control in industrial environments remains constant. However, more companies are now taking a much closer look at developing or updating specifications due to the changes made by controls manufacturers to comply with the RoHS restrictions on the use of lead. This includes specifying an ISA Class G1 environment for control rooms, etc., where in the past a Class G2 environment was considered acceptable. Specifications are also now showing up requiring the measurement and quantification of silver corrosion rates and related corrosion products.

With a majority of control systems, manufacturers opting to use the ImmAg process for their PCBs and other electrical components, and the fact that silver is much more sensitive to lower levels of corrosive gases, we have already seen increased concerns over equipment reliability. As one Automation Engineer for an Australian pulp and paper manufacturer described it, “The ISA Standard is becoming irrelevant because it does not take into account silver corrosion. All of the new equipment I have purchased over the last year contains silver and the failure rate for some components is now being measured in weeks instead of years.”

Another contributing factor to concerns over the use of silver in industrial applications is that even with tightening the environmental control requirements for temperature and humidity and the positive effect this has on copper corrosion, silver can still exhibit high rates of corrosion in well-controlled environments. Examination of one environmental reactivity coupon (ERC) database has shown that in locations reported as ISA Class G1 for copper corrosion, the corresponding silver corrosion rate can be up to 10x higher. Furthermore, every ERC analyzed shows evidence of sulfur contamination (as silver sulfide, Ag₂S). On average, the amount of silver corrosion measured is double that of the copper corrosion reported.

Corrosion control in industrial environments is acknowledged as a requirement to assure electrical and electronic equipment reliability. However, up to now corrosion control in non-industrial applications has only been a concern in isolated instances. Desktop and laptop computers, servers, data communications (datacom) equipment and other equipment used in information technology (IT) applications were not particularly sensitive to the types and concentrations of contaminants present in urban environments. However, even these types of computer equipment are now at risk due to RoHS.

Datacom equipment center owners and operators have traditionally focused most of their attention on the physical structure and performance of the data center infrastructure (e.g. power, cooling, raised access floor equipment). Most IT hardware is designed to operate in a controlled environment. There are few moving parts (air handling equipments, drive motors, etc.) and electronics are not expected to simply “wear out.”

High reliability is demanded for today’s IT equipment and projections to first failure are more than 11 years of power on operation, which is far longer than in the real world, especially when considering that the equipment becomes obsolete in half that time. However, that high reliability is only if the product is maintained in the optimum environment. Any site climate deviations or deviations in electrical power, static electricity or air quality will have a negative impact on the equipment and failure rates.

Even though today’s complex and sensitive IT equipment requires a higher level of environmental control for gaseous contamination than would have been considered before RoHS took effect, this has been one aspect of data center environmental control that was mostly overlooked. Datacom equipment center contamination if left unchecked can influence the reliability and the continuous operation of mission critical IT equipment within a facility. Gaseous contamination can result in intermittent equipment glitches, unplanned shutdowns, or failure of critical systems that often result in significant business and financial loss. Harsh environments are also not always obvious or restricted to industrial settings.

Contaminant gases containing sulfur, such as SO₂ and H₂S, are the most common gases in data centers causing hardware corrosion. One example of component failure was due to sulfur gases entering a component package and attacking the silver resulting in the formation of Ag₂S. The mechanical pressure

created by the Ag₂S formation inside the package damaged its mechanical integrity and caused the device to fail. This and other failure mechanisms are becoming common occurrences within data centers using RoHS-compliant equipment and components produced using the ImmAg process, and to a lesser degree, the ENIG process.

To maintain a high level of equipment dependability and availability, it should be understood that a data center is a dynamic environment where many maintenance operations, infrastructure upgrades, and equipment change activities occur on a regular basis. Airborne contaminants harmful to sensitive electronic devices can be introduced into the operating environment in many ways (e.g., chlorine can be emitted from PVC insulation use on wires and cables if temperatures get too high.) However, the outdoor ambient air that is used for both cooling and pressurization is often the primary source of corrosive contaminants and should be cleaned before its introduction into the data center environment. And now with the rediscovery of “free cooling” using air-side economizer technology, more outside air will be brought into the data center and along with it higher levels of contamination than previously encountered. Loosening control limits for humidity will also contribute an increased potential for corrosion-related problems.

With the changes to IT equipment due to the RoHS directives, data center designers, managers, and operators should include an environmental contamination monitoring and control section as part of an overall site planning, risk management, mitigation, and improvement plan.

Included in this plan should be considerations for the assessment of the outdoor air and data center environment with regards to corrosion potential. Even though ISA 71.04 is considered a standard for industrial applications, it still has relevance in datacom applications and can be used to provide site-specific data on the types and levels of gaseous contamination. ERCs can be used as a survey tool to establish baseline data necessary to determine if and what type of environmental controls are needed.

The second part of the plan should be the development and specification of a specific contamination control strategy. Corrosion in an indoor environment is most often caused by a short list of contaminants or combinations of a few contaminants. The compounds present in an individual data center are highly dependant on the location and the controls put in place to mitigate them. Most often this would involve the selection and application of the appropriate chemical filtration systems to clean both the outdoor ventilation air as well as the air inside the data center.

The final part of the plan would be to establish a real-time environmental monitoring program based on the severity levels established in the ISA Standard. Real-time environmental reactivity monitors (ERMs) can provide accurate and timely data on the performance of the chemical filtration system as well as the air quality within the data center itself.

The absence of gaseous contamination controls can be the result of a lack of knowledge and education. Often the relationship between corrosion levels and hardware failures in data centers is overlooked or unknown. However, due to the efforts of companies like Rockwell, Dell, IBM, HP and others, this knowledge gap is shrinking and successful corrosion monitoring and control programs can be developed and implemented – assuring reliable operation of data center equipment.

SUMMARY AND CONCLUSIONS

Most computer systems and associated components, such as telecommunications and storage systems used in data centers are protected against the potential threats posed by fire, power, shock, humidity, temperature and particulate contamination. Unfortunately, the potential damage to this equipment caused by the corrosive effects of gaseous contaminants due to RoHS compliance has still not been fully recognized or addressed.

Manufacturers have to comply with RoHS if they want to continue to do business in the EU, China, etc., and many have taken the ImmAg route as their path to compliance. This has taken care of one issue but has presented new challenges with regards to equipment reliability.

The first stages of corrosion may show up as untraceable alarms, as corrosion products grow and provide random circuit paths that clear themselves as soon as current flows through them. However, some information may have already been lost. In the worst cases, substantial resistance to current flow is developed, variations in voltages occur, and the entire circuit may become useless due to changes in component value. These circuit failures, whether in a server, hard disk drive, switch, or other electrical component, increase equipment capital cost and warranty and maintenance costs. Something as simple as a corroded chip may destroy the promise of real-time connectivity, resulting in consumer dissatisfaction and lost profit.

Recognizing the severity of the problem, most of the world's leading manufacturers of computer systems have placed in their site planning manuals references to the ISA or similar standards for acceptable levels of airborne contaminants. This is because they provide achievable and effective guidelines to protect electronics and electrical equipment from the damaging effects of corrosive gases.

The use of reactivity monitoring using both copper and silver corrosion data is being used to provide a more complete environmental assessment than the copper-only monitoring described in ISA Standard 71.04-1985. This is based on studies that have shown that while copper coupons may be good indicators of corrosive gases in an environment, they are not sufficiently sensitive in all cases to many of the contaminants encountered in many environments (Muller 1991, Muller et al 1991). The standard is currently undergoing a long past-due update to incorporate the use of silver corrosion data into quantifiable severity levels relating to equipment reliability. It is also planned to add the use of real-time reactivity monitors as an acceptable approach for environmental classification using reactivity monitoring. Most likely this will be a reference to mass-gain monitoring techniques (e.g., quartz crystal microbalances).

When both copper and silver monitoring is used and the copper reactivity is equal to an ISA G1 classification, the corresponding silver corrosion rate can be expected to be approximately double that of the copper coupon for indoor environments (Purafil 2000). Therefore, total silver corrosion less than 600Å **with no evidence of chlorine contamination** (as AgCl), would be considered an acceptable complement to a class G1 copper environment with **no evidence of sulfur contamination** (as Cu₂S). Total silver corrosion above 600Å with or without evidence of chlorine often indicates an environment where the effects of corrosion are measurable and there is an increased probability of corrosive attack.

The issue and potential for corrosion-related problems in data centers has been presented. Data from many different sites shows that corrosive atmospheres exist in locations that most would consider otherwise benign if not for the changes in electronics mandated by RoHS legislation. These problems can be addressed by continuous monitoring of the data center environment and removal of corrosive contaminants where indicated. Ultimately, the successful implementation of a corrosion protection program requires:

- Knowledge and understanding that corrosion of electronic equipment is a serious problem.
- Commitment to a monitoring program to describe the potential for electronic equipment failure.
- Commitment to an integrated contamination control system.
- Commitment to take corrective action whenever necessary.

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