

How the Changing Regulatory Landscape is Affecting Equipment Reliability

Grant Crosley

Visy Pulp and Paper, Campbellfield VIC Australia

Chris Muller

Purafil, Inc., Doraville, Georgia, USA

ABSTRACT

The European Union directive 2002/95/EC “on the **R**estriction of the use of certain **H**azardous **S**ubstances in electrical and electronic equipment” (RoHS) was implemented in July 2006. This was the first of many regulations with the shared aim of the elimination of lead in electronic products. However, ongoing research has shown that printed circuit boards made using lead-free materials can be more susceptible to corrosion and that lead-free products with immersion silver (ImmAg) surface finish are particularly susceptible to corrosion in high sulfur environments – the same environments found in pulp and paper manufacturing.

This paper will discuss RoHS compliance issues and the resulting potential for corrosion-related problems. Data will be presented that illustrates corrosive environments exist in locations that would otherwise be considered benign if not for the changes in electronic equipment mandated by RoHS legislation. However, these problems can be addressed by continuous monitoring of the environment and the control of corrosive contaminants where indicated. Ultimately, the successful implementation of an electronic equipment reliability program requires; (1) knowledge and understanding that corrosion of electronic equipment is a serious problem, (2) commitment to a monitoring program to describe the potential for electronic equipment failure, (3) commitment to an integrated contamination control system, and (4) commitment to take corrective action whenever necessary.

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, now 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 Restriction of the use of certain Hazardous 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.

RoHS – THE EU AND BEYOND

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 than those passed in the EU. As described by a potentially-impacted customer: “Without exemptions, it is impossible to build a compliant board” [1]. Although, the regulations are different and are based on different processes, the aims are similar. Convergence of the regulations is not foreseen at present, as it would require high-level negotiations between the EU and China and changes of approach [2].

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.
- Australia is conducting a survey.
- Brazil senate bill PL 173/2009 proposes RoHS for all computer and IT equipment sold in Brazil.
- Japan Green Procurement Survey Standardization Initiative (JGPSSI) adopted “RoHS” labeling requirements for certain products.
- Korea is considering RoHS legislation.
- Taiwan has a voluntary RoHS program.

U.S. State bills:

- California SB20/SB50 – “Covered Electronic Waste Payment System” 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.
- Maine – Title 38, Chapter 16, § 1610 “Electronic waste”
- Minnesota – patterned after EU RoHS, however only for consumer products.
- Several other states are looking at RoHS legislation (see Figure 1).

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.

* 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.

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.

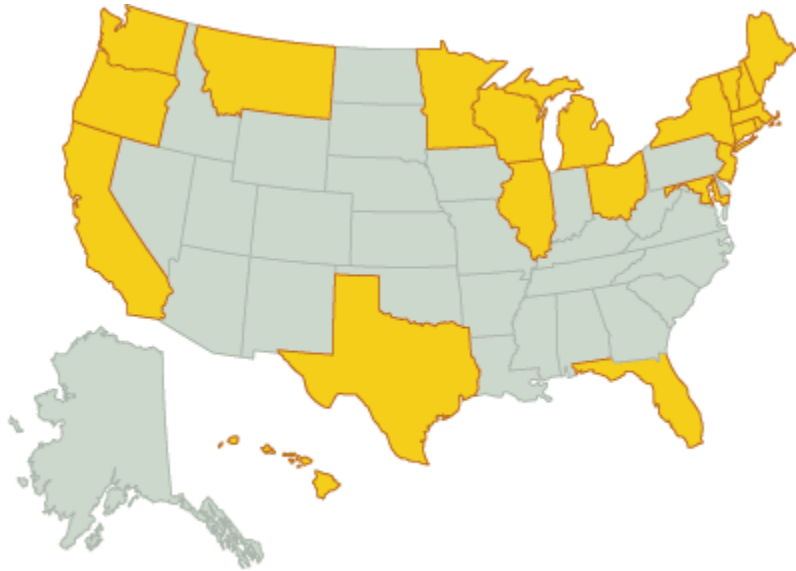


Figure 1. Colored areas denote active or pending RoHS legislation

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 becoming the standard PCB finish in the electronics industry [3].

Immersion silver would seem to have a bright future under RoHS [4]. 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 Instrument Society of America (ISA) Standard 71.04 [5] 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 (Table I). G1 is benign and GX is open-ended and the most severe.

Table I. Classification of Reactive Environments

Class	Severity Level	Copper Reactivity [†]	Comments
G1	Mild	<300Å	An environment sufficiently well-controlled such that corrosion is not a factor in determining equipment reliability.
G2	Moderate	<1000Å	An environment in which the effects of corrosion are measurable and corrosion may be a factor in determining equipment reliability.
G3	Harsh	<2000Å	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.
GX	Severe	≥2000Å	An environment in which only specially designed & packaged equipment would be expected to survive. Specifications for equipment in this class are a matter of negotiation between user & supplier.

[†] Corrosion rates are reported as the total copper film thickness in angstroms (Å) normalized to a 30-day exposure.

In a study performed by Rockwell Automation [6] 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.” 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) [7]. This is the equivalent of an ISA Class G3 severity level.

THE REALITY OF RoHS

Corrosion-induced failures have been and continue to be 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 (Cu_2S) 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. Silver 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 paper mill environments. More than twenty years ago manufacturers of distributed control systems (DCS) such as Digital Equipment Corporation (DEC), ABB, and Honeywell described their concerns regarding equipment corrosion in research documents, technical papers, and site planning guides. These companies also provided guidance in terms of environmental conditions necessary to protect their computer equipment (Figure 2).

Manufacturers of industrial computer equipment still specify the control of corrosive gases in their site planning guides and/or the terms and conditions

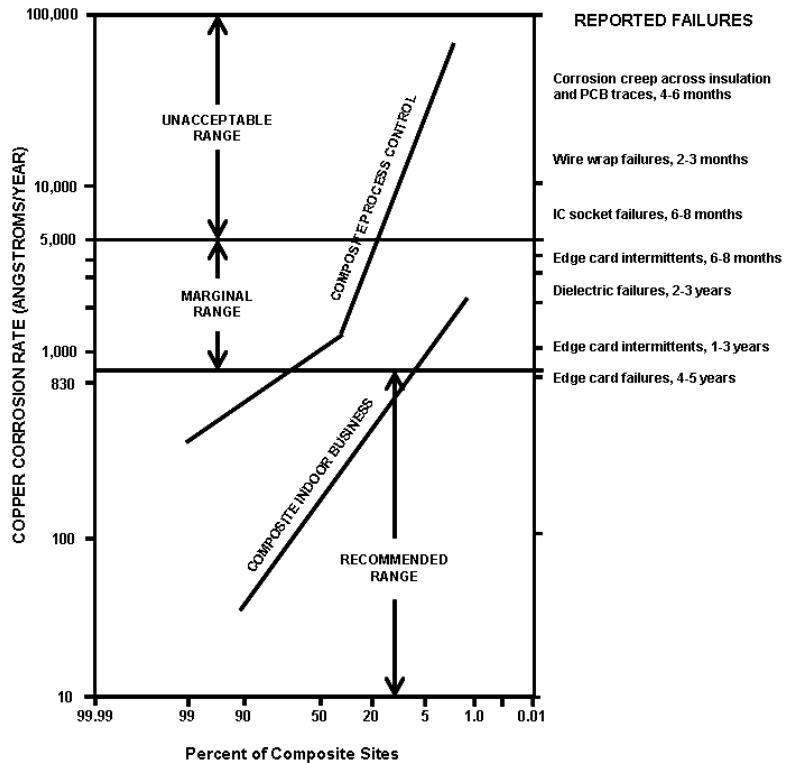


Figure 2. Copper corrosion rate distribution guidelines [8].

necessary to maintain warranties and service contracts. Even in environments previously considered benign with regards to electronics corrosion serious problems as a direct result of RoHS compliance are being reported.

One failure mechanism caused by the lead-free transition was not foreseen by the industry. It was soon discovered that lead-free products with an immersion silver (ImmAg) surface finish will creep corrode in what some electronic equipment manufacturers consider to be 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 documented several case studies where creep corrosion of ImmAg finish caused failures of computer systems in high sulfur environments (Mazurkiewicz 2006). 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 [9].

Analysis revealed the corrosion products to be copper sulfide (Cu_2S) and silver sulfide (Ag_2S). High amounts of Cu_2S typically indicate the presence of active sulfur compounds such as elemental sulfur (S), hydrogen sulfide (H_2S), or organic sulfur compounds such as mercaptans. Ag_2S can also be formed by these contaminants but can also be formed by exposure to sulfur oxide (SO_x) contamination.

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) [10].

Corrosion-induced failures are frequent in electronic products used in these environments with a typical failure mechanism being the reaction of atmospheric sulfur with exposed metals – particularly copper and silver. Corrosion can occur quite rapidly in humid environments especially in the presence of small amounts of atmospheric sulfur and chlorides resulting in (among other things) intermittent equipment malfunctions, unplanned shutdowns, or failure of critical systems.

Recognizing the severity of the problem, most of the world's leading manufacturers of process measurement and control systems require that customers use the International Society for Automation (ISA) Standard ISA-71.04-1985 or other similar standards to determine levels of airborne contaminants to maintain warranties and service contracts. These standards provide achievable and effective guidelines to protect electronics and electrical equipment from the damaging effects of corrosive gases. They classify environmental severity levels for electrical and electronic systems and provide a measure of the corrosion potential of an environment typically defined in terms of the rate at which they react with copper. However, with the passage of RoHS legislation, and the switch to lead-free finishes such as ImmAg, many control systems manufacturers and end-users are now questioning whether this copper-only environmental monitoring is adequate or is even still relevant.

Although silver is not an equipment reliability determinant in the ISA standard, it has been long been included as part of environmental monitoring programs. Reactivity (corrosion) monitoring using both copper and silver corrosion data provide a more complete environmental assessment than the copper-only monitoring described in Standard 71.04. This standard is currently undergoing a long past-due update to incorporate the use of silver corrosion data into quantifiable severity levels that directly relate to equipment reliability.

For instance, some environments that are non-corrosive to copper, and thus considered harmless to equipment (by the ISA standard), are 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 problems. Much of the new equipment purchased and installed over the last couples of years contains silver due to RoHS compliances and failure rates for some components are now being measured in weeks instead of years.

Corrosive gases have been and continue to be a problem in the paper industry. The use of recycled fiber is increasing at the same time that electrical and electronic equipment is becoming more sophisticated and complex. Significant quantities of corrosive gases are being generated from the paper making process and the equipment required to

maximize process efficiency is being adversely affected. Direct and indirect costs of failures due to corrosion run into many hundreds of thousands of dollars a year at individual mills. Corrosion is also an increasing safety concern, particularly on higher voltage systems.

There is a growing concern in pulp and paper and other process industries that using copper-only reactivity monitoring results can seriously underestimate the potential for equipment failure in these environments. And now due to RoHS compliance, many environments previously considered benign with regards to electronics corrosion are experiencing serious problems. Electronic equipment manufacturers have to comply with RoHS and many have taken the ImmAg route as their path to compliance. This has taken care of one issue – the elimination of lead – but has presented new challenges with regards to equipment reliability.

RoHS AND RELIABILITY

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 the related corrosion products.

With many 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 the National Reliability Manager for one 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 purchased over the last year contains silver and the failure rate for some components is now being measured in months instead of years.”*

Problems with RoHS-Compliant Equipment

A recycled paper mill began a project in 2006 to replace obsolete equipment that could no longer be supported (no manufacturer technical support, lack of spares, etc.) with new DCS and programmable logic controls (PLCs). The original hardware had been installed for 15 years and had proven to be reliable and robust. One contributing factor to this was the fact that many of the locations where this equipment had been installed were classified as ISA Class G1 for copper. However, the corresponding silver corrosion rates were up to 20x higher and essentially all of the silver corrosion reported from the analysis of corrosion classification coupon (CCCs) collected over several years was due to sulfur corrosion. This presented some concern based on changes to the equipment due to RoHS compliance.

Before starting the replacement program, mill staff was very aware of copper corrosion and the reliability risks associated with exceeding the ISA severity levels specified by the equipment manufacturers. Routine CCC monitoring results showed that copper corrosion was significant but not extreme in many locations; however, the corresponding silver corrosion rates were routinely much higher. On average the silver corrosion rate was 10x that for the corresponding G1 copper rate (Table II).

Within three months of replacing the old systems, the mill began experiencing frequent failures of the input/output (I/O) stations installed on the process fieldbus (PROFIBUS).[‡] A lot of work was put into making the PROFIBUS installations error-free, and the architectures were reengineered to follow the core rules precisely (i.e., the systems were pulled back to very simple, straight-line installations).

These I/O stations or nodes have a number of I/O modules attached to them and communicate the inputs and outputs over the PROFIBUS with the DCS. Since the problems were intermittent and symptoms appeared related to PROFIBUS communication or installation, a full diagnostic process was implemented to capture any and all information about each failure. This included examination of the hardware, the hardware location, its position on the

[‡] PROFIBUS is the dominant fieldbus, with more than 4.8 million of these installed in the process industries by the end of 2008. Utilizing a single-cable “bus” structure, fieldbus eliminates hardwiring in the automation of production lines (<http://www.profibus.com/>).

bus, architectures, and software settings. Through systematic investigation and analysis, several potential causes were eliminated and root cause analysis for the remaining issues was performed.

Table II. Paper Mill CCC Analysis Results[§]

Location	Cu ₂ S	Cu ₂ O	CuUnk	Copper Total	ISA Class	AgCl	Ag ₂ S	AgUnk	Silver Total
DC Drive Room	0	142	0	142	G1	0	2455	0	2455
DC Drive Room	961	201	0	1162	G3	0	4909	0	4909
DC Drive Room	2303	975	0	3278	GX	0	3704	0	3704
DCS Room	0	118	0	118	G1	0	1590	0	1590
Electrical Room	0	81	0	81	G1	0	1636	0	1636
Motor Control Center D	275	95	0	370	G2	0	1964	0	1964
Motor Control Center H (1)	533	131	0	664	G2	0	1289	0	1289
Motor Control Center H (2)	518	144	0	662	G2	0	1269	0	1269
Motor Control Center H (3)	396	85	0	481	G2	0	438	139	577
Motor Control Center H (4)	212	45	0	257	G1	0	1460	0	1460
Paper Machine MCC	152	65	0	217	G1	0	1590	0	1590
Paper Machine Rack Room	509	142	0	651	G2	0	1932	0	1932
PLC Room	1263	159	0	1422	G3	0	4009	0	4009
Server Room	0	106	0	106	G1	0	1870	0	1870
Winder Motor Control Center	160	55	0	215	G1	0	1621	0	1621

Mill staff recognized that the resistance of a choke installed on the base unit of the I/O station to eliminate signal noise was increasing and on failed units was a high or open circuit. Ironically enough this choke was only installed to meet other European legislation pertaining to radio frequency interference (RFI) emissions. The critical issue identified pertaining to this choke was that it is an electronic chip design with a very thin layer of silver on the IC legs in compliance with the lead-free regulations of RoHS. Corrosion of this silver layer destroyed the choke's connection to the printed circuit and hence the high resistance. Consultation with the manufacturer confirmed the presence of silver on the chokes.

The mill was already in the process of installing air cleaning equipment to remove corrosive gases from the air and reduce the rates of copper corrosion, however, the extremely short time to failure for these silver-containing components accelerated this effort in order to prevent additional failures. Staff is confident that these failures were purely the results of RoHS compliance and the use of silver. The lack of information and warnings by the supplier regarding potential issues related to their RoHS compliance programs is troubling considering that even when presented with this evidence, they still concluded these failures were due to "installation errors."

Potential Problems Exist at all Mills

CCC data from several additional mills (Table III) show that many locations exhibiting an ISA Class G1 environment for copper have silver corrosion rates that would indicate serious cause for concern for any electronic equipment using an ImmAg surface finish specifically or any silver or silver-plated components in general.

Another contributing factor to concerns over the increased use of silver in industrial applications is that even with tightened control requirements for other environmental parameters (e.g., temperature and humidity) and the positive effect this has on the rate of copper corrosion, silver can still exhibit high rates of corrosion even in well-controlled environments. Closer examination of this CCC database shows that in locations reported as ISA Class G1 for copper corrosion, the corresponding silver corrosion rate can be up to 10x higher. Furthermore, **every** CCC analyzed shows evidence of sulfur contamination (as Ag₂S). On average, the amount of silver corrosion measured is double that of the copper corrosion reported [11].

[§] The total corrosion measured is actually the sum of individual corrosion films: Cu₂S = copper sulfide, Cu₂O = copper oxide, CuUnk = copper unknowns, AgCl = silver chloride, Ag₂S = silver sulfide, AgUnk = silver unknowns. All data is normalized to a 30-day exposure.

Table III. Pulp and Paper Mill CCC Data [11]

Location	Area/Room	Cu ₂ S	Cu ₂ O	CuUnk	Copper Total	ISA Class	AgCl	Ag ₂ S	AgUnk	Silver Total
Austria	AHU Room	0	180	0	180	G1	0	3142	0	3142
	DCS Room	182	78	0	260	G1	0	3491	0	3491
	Electrical Room	115	46	0	161	G1	0	1582	0	1582
Brazil	Control Room	192	101	0	293	G1	0	1042	0	1042
	Operations Room	205	88	0	293	G1	0	1234	0	1234
	MCC	0	125	0	125	G1	0	948	0	948
China	DCS Room	182	104	0	286	G1	0	1022	0	1022
	Wet End Control	182	78	0	260	G1	0	1118	0	1118
	Computer Room	124	44	0	168	G1	0	5467	0	5467
Finland	DCS Cabinet	0	118	0	118	G1	0	1636	0	1636
	MCC	0	106	0	106	G1	0	2634	0	2634
	Control Room	0	150	0	150	G1	0	2796	0	2796
Holland	Mechanical Room	0	68	0	68	G1	0	2182	0	2182
	Server Room	0	78	0	78	G1	0	1964	0	1964
	Splicer Room	0	105	0	105	G1	0	1145	0	1145
Japan	Control Room	0	173	0	173	G1	0	1497	0	1497
	IPC Room	0	231	0	231	G1	0	2145	0	2145
	DCS Room	215	62	0	277	G1	0	1038	0	1038
Korea	DCS Panel	187	61	0	248	G1	0	1848	0	1848
	MCC Room	204	56	0	260	G1	0	1810	0	1810
	PLC Panel	102	50	0	160	G1	0	1155	0	1155
USA	Electrical Room	172	34	0	206	G1	35	1315	0	1340
	Wet End Drives	196	81	0	277	G1	0	1565	0	1565
	Control Room	175	86	0	261	G1	0	5073	0	5073

Contaminant gases containing sulfur, such as SO₂ (sulfur dioxide) and H₂S, are the most common gases in paper mills, refineries, chemical plants, etc. that cause hardware corrosion and corrosion control in industrial environments is acknowledged as a requirement to assure electrical and electronic equipment reliability. One example of component failure is from 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 [12]. This and other failure mechanisms are becoming common occurrences when using RoHS-compliant electronic 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 control room 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 in addition to the ventilation system. For instance, chlorine can be emitted from PVC insulation use on wires and cables if temperatures inside the DCS cabinets get too high. However, it is still the outdoor ambient air used for cooling and pressurization that remains the primary source of corrosive contaminants and it should be cleaned before its introduction into the control room environment.

With the changes to process control equipment due to the RoHS directives, plant 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 indoor environment with regards to corrosion potential. ISA Standard 71.04 can be used to provide site-specific data on the types and levels of gaseous contamination and the amount of corrosion being formed. CCCs 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 chemical contaminants or

combinations of contaminants. The contaminants present in a specific room are highly dependant on 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 indoor air.

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 Atmospheric Corrosion Monitors (ACMs) or Continuous Corrosion Transmitters (CCTs) can provide accurate and timely data on the performance of the chemical filtration system as well as the room air quality [13].

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 control rooms is overlooked or unknown. However, due to the continuing efforts of companies like ABB, Dell, Honeywell, HP, IBM, Rockwell, Siemens, and others, this knowledge gap is shrinking and successful corrosion monitoring and control programs are being developed and implemented – assuring reliable operation of process measurement and control equipment.

New manufacturing techniques using much thinner conductive components than in previous generations of this equipment, the use of silver as a primary surface finish, and the lack of silver standards from ISA are all contributing factors to an increased risk for electronic process measurement and control equipment used in a paper mill environment. Further, the general lack of information from manufacturers regarding the changes made for RoHS compliance and any resulting reliability issues means that environmental monitoring and contamination control will be mandatory to assure reliable performance and profitable operations.

ONGOING AND FUTURE WORK

The amount of corrosion forming over any given period is a primary indicator of how well-controlled an environment may be. It has been proven that if an environment exhibits a reactivity rate of $<300\text{\AA} / 30$ days for each copper (ISA Class G1) – without evidence of sulfur contamination (as Cu_2S) and silver corrosion – without chlorine contamination (as AgCl) – there is little else that can be done, economically, to improve the environment.

Examination of corrosion data from copper and silver CCCs makes it more and more apparent that one cannot accurately determine the true corrosive potential of an environment when following the current methodology of ISA Standard 71.04. This copper-only corrosion monitoring will not and cannot conclusively determine the presence or absence of environmental chlorine or sulfur oxides, and it only provides circumstantial evidence of whether silver corrosion is occurring or not.

The fact that the ISA Standard does not take silver corrosion into account when assigning severity levels poses a serious dilemma for those charged with the operation and maintenance of critical process control equipment. If monitoring indicates a Class G1 environment (for copper) but there are high levels of silver corrosion, does one go about their business and assume that the environment poses no threat to their electronic equipment? Or do they use silver corrosion monitoring as evidence of an increased risk potential for those components that are now RoHS compliant? These questions are being asked and many are working to provide the answers.

The authors are involved with current efforts to update the ISA Standard to include silver corrosion monitoring as a requirement in developing environmental severity levels. The first changes will most likely be to require the use of both copper and silver for environmental assessments with the silver data used both qualitatively (e.g., sulfides present/absent, chlorides present/absent) and quantitatively. Additionally, the $\text{Ag}_2\text{S}/\text{Cu}_2\text{S}$ ratio can be used to indicate humidity effects.

RoHS is Here to Stay

RoHS costs have been conservatively estimated at \$8B industry-wide, yet whether restricting the use of these substances yields even \$8B worth of positive environmental impact is questionable [14]. However, the fact remains that there is a perceived environmental benefit to eliminating the lead in the HASL process. Manufacturers of electrical and electronic equipment have to comply if they want to continue to do business in the EU, China, and other countries, 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.

Assuring long-term equipment reliability requires working with plant personnel to quantify the corrosive potential of an environment towards the various types of electronic equipment in use, providing engineered solutions for gaseous contaminant control, and ongoing monitoring of the controlled environment to assure compliance with standards and specifications. The successful application of such a corrosion control program in pulp and paper mills, refineries, chemical plants, and many other industrial settings will protect critical process measurement and control equipment and assure profitable manufacturing operations.

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