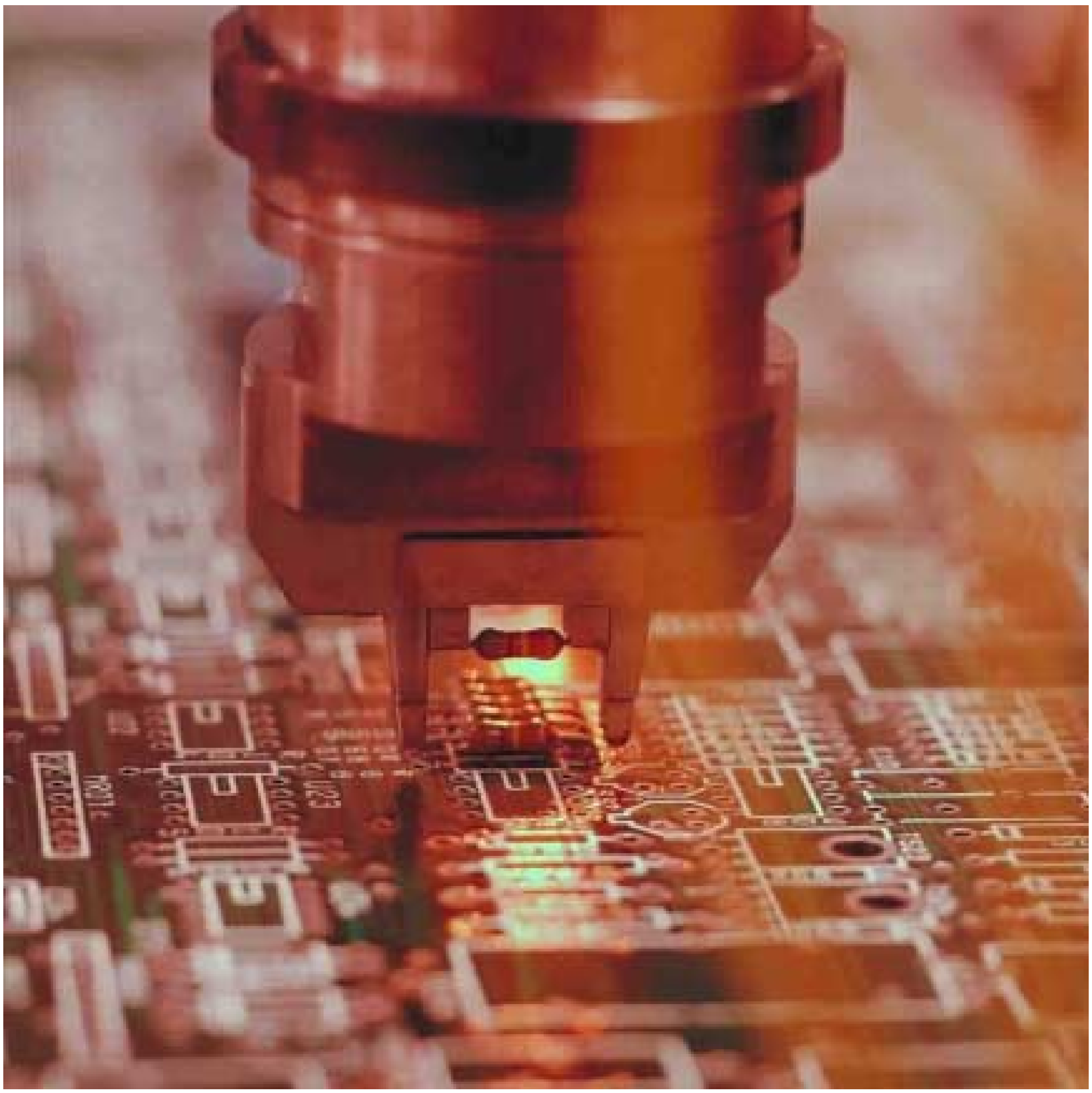
APPENDIX Z

ELECTRONICS



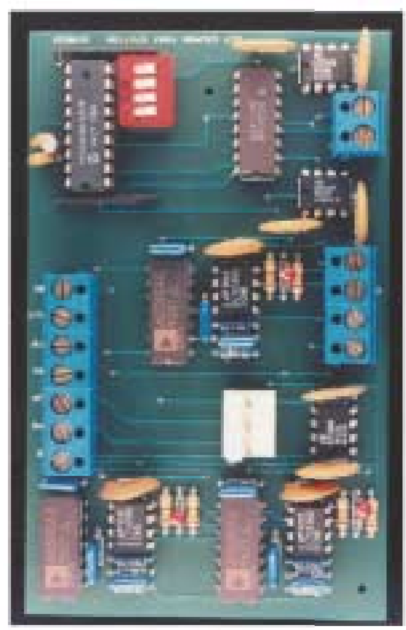

Instrumentation


On-line monitoring


Connections to strain gauges


Laboratory equipment


Office electronics


Circuit board


Electronic testing equipment

APPENDIX Z

ELECTRONICS

MARK YUNOVICH[1]

SUMMARY

Corrosion in electronic components manifests itself in several ways. Computers, integrated circuits, and microchips are now an integral part of all technology-intensive industry products, ranging from aerospace and automotive to medical equipment and consumer products, and are therefore exposed to a variety of environmental conditions. Corrosion in electronic components is insidious and cannot be readily detected; therefore, when corrosion failure occurs, it is often dismissed as just a failure and the part or component is replaced.

Because of the difficulty in detecting and identifying corrosion failures, the cost of corrosion is difficult to determine. Arguably, in many instances, particularly in the case of consumer electronics, such devices would become technologically obsolete long before corrosion-induced failures. In addition, while corrosion-related user costs due to irretrievably lost data could be staggering, as the electronic information and data exchange become more intensive, most sensitive information is frequently backed up. Capital-intensive industries with significant investments in durable equipment with a considerable number of electronic components, such as the defense industry and the airline industry, tend to keep the equipment for longer periods of time, so that corrosion is likely to become an issue. Although the cost of corrosion in the electronics sector could not be estimated, it has been suggested that a significant part of all electric component failures may be caused by corrosion.

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[1] CC Technologies Laboratories, Inc., Dublin, Ohio.

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SECTOR DESCRIPTION

Corrosion of electronic components manifests itself in several ways. Computers, integrated circuits, microchips, etc. are now an integral part of all technology-intensive industry products, ranging from aerospace and automotive to medical equipment and consumer products, and are therefore exposed to a variety of environmental conditions.

As electronics become more and more ubiquitous and the devices more robust, concern over the operating environment seems to lessen, particularly in the personal computer (PC) market. Desktop computers can now be found in most homes and the vast majority of businesses. Availability of sub-$1,000 computers has effectively made them a commodity. In 1989, an estimated 21 million PCs were sold worldwide, approximately 9 million of them in the United States. In 1998, worldwide PC sales totaled almost 93 million and U.S. sales approximately 36 million. In 1990, almost 15 percent of U.S. households owned a computer. In 1999, nearly 50 percent of U.S. households owned a computer.(1) Personal use accounts for only approximately 30 percent of PC sales, while businesses, the government, and schools represent the rest.

The trend toward miniaturization of technology has led to the development of small personal electronic devices, such as pagers, cellular phones, and palm-sized personal organizers and computers. The PalmPilot was released in 1996 and by mid-1999, three million units had been sold.(2)

In 1999, more than 98 percent of 101 million American households had a television set. VCRs could be found in 80 percent of those households, and more than 94 percent of the households had telephones.(3) Most of the other household appliances, from toasters to washers, are controlled by electronic modules. In addition, there were 4,782 AM radio stations, 5,745 FM radio stations, and 1,599 television stations. The majority of the 200 million automobiles currently in use also have electronic components. Some of the statistics on consumer electronics are summarized in table 1.

Table 1. Household/consumer electronics statistics.

Cable TV households	1998	74,550,000
Total TV households	Jan. 1999	99,400,000
TV households with two or more sets	Jan. 1999	74%
TV households with VCRs	1997	74%
Households with video game consoles	1995	40%
Internet users per 1,000 people	1998	283

The short span needed for market penetration for some of the modern devices, along with the ownership data, is shown in figure 1.(4) Note the short span needed for cellular phones to become a common device, compared to that of an ordinary telephone.

According to some publications, America Online's system "conveys 760 million" email messages per day, twice as many as the letters handled by the U.S. Postal Service.(5)

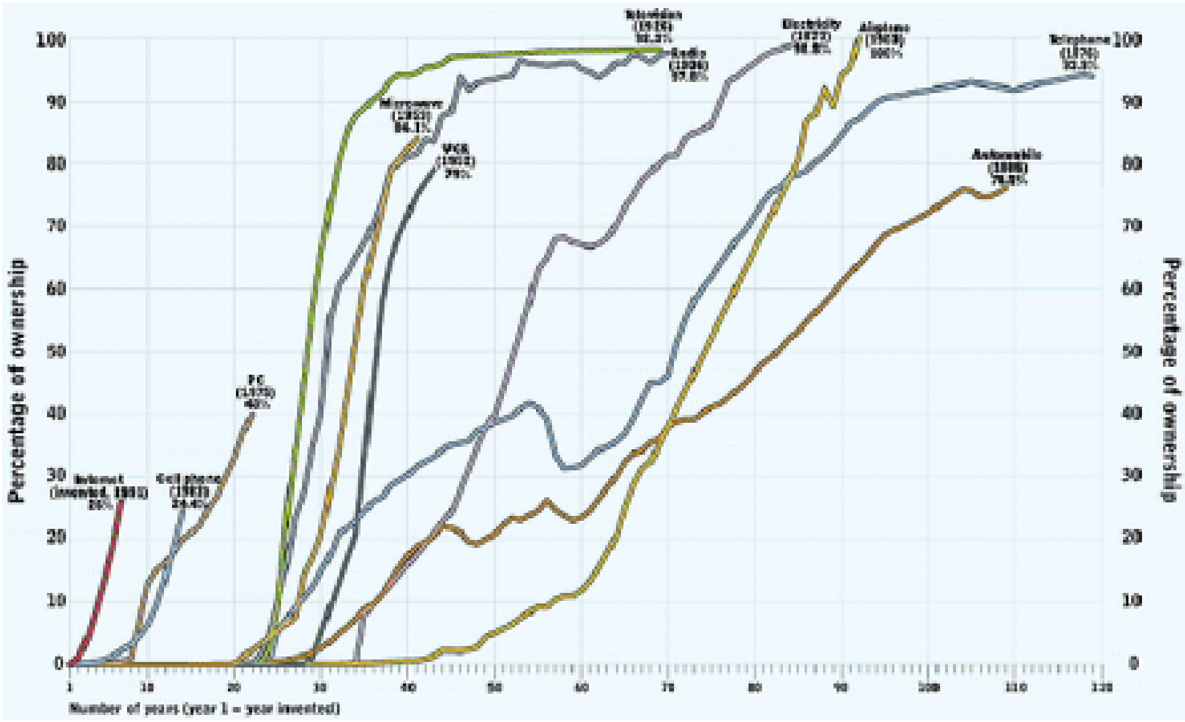

Figure 1. "Time-to-ownership" for some electronic devices.

The value of automotive electronic components manufactured in 1997 was estimated at $1.4 billion.[(6)] According to the U.S. Census Bureau,[(7)] during 1999, the total value of shipments for consumer electronics (excluding computers) was $8.2 billion, an increase of 4.6 percent from the 1998 value of $7.8 billion. Automotive audio equipment increased 15.7 percent from $941.5 million in 1998 to $1.1 billion in 1999. Shipments of television receivers increased 9.6 percent from $3.9 billion in 1998 to $4.3 billion in 1999. All other consumer audio and video equipment shipments decreased 16.7 percent in 1999 from $827.2 million in 1998 to $689 million in 1999. Loudspeakers, microphones, kits, and public address systems decreased 1.3 percent from $2.1 billion shipped in 1998.

The U.S. Census Bureau reported the 1997 value of shipments in the Manufacturing – Industry Series.[(1)] Table 2 shows a summary of the value of shipments for various industries that manufacture electronics. This table is not all-encompassing, and components that are manufactured in one industry are used in another. If the shipment values for the electronics manufacturing industries listed on this table are summed, a total value of $335.8 billion per year can be estimated. The table shows that the manufacturing of semiconductors and related devices, and the manufacturing of computers are the largest industries. Broadcasting equipment, including radio, television, and wireless communications equipment, and telephone apparatus manufacturing have significant shipments as well.

Table 2. Industry statistics for electronics manufacturing industry in 1997, according to the U.S. Census Bureau.[8]

ELECTRONICS MANUFACTURING INDUSTRIES	**1997 TOTAL VALUE OF SHIPMENTS**	
	$ x billion	**%**
Semiconductor and Related Device Manufacturing	78.0	23.2
Electronic Computer Manufacturing	65.9	19.6
Radio and Television Broadcasting and Wireless Communications Equipment Manufacturing	39.5	11.8
Telephone Apparatus Manufacturing	37.8	11.3
Other Computer Peripheral Equipment Manufacturing	26.9	8.0
Printed Circuit Assembly (Electronic Assembly Manufacturing)	25.6	7.6
Computer Storage Device Manufacturing	13.3	4.0
Other Electronic Component Manufacturing	10.4	3.1
Bare Printed Circuit Board Manufacturing	9.6	2.9
Audio and Video Equipment Manufacturing	8.2	2.4
Electronic Connector Manufacturing	5.7	1.7
Other Communications Equipment Manufacturing	4.2	1.3
Electron Tube Manufacturing	3.8	1.1
Electronic Capacitor Manufacturing	2.5	0.7
Electronic Coil, Transformer, and Other Inductor Manufacturing	1.6	0.5
Computer Terminal Manufacturing	1.5	0.4
Electronic Resistor Manufacturing	1.3	0.4
TOTAL	**$335.8**	**100.0%**

CAUSES OF CORROSION

The most common electronic components include integrated circuits (IC), printed circuit (PC) boards, and connectors and contacts. Traditional materials used for IC conductors are aluminum-based alloys, often alloyed with silicon and copper. Major metallic components in PC boards, such as conductors and connectors, are typically made of copper where soldering is done with lead-tin alloys. Contacts are commonly manufactured from copper covered with electroplated nickel or gold for improved corrosion resistance.

As electronic devices become more and more common, they become increasingly exposed to much harsher conditions than the air-conditioned rooms used to house early computers. Although the microchip in an automobile, for example, is not directly subjected to the same hazards as the car body, given the dimensions of the former (silicon-based integrated circuit elements are spaced less than 0.2 microns), the tolerance for corrosion loss is much smaller (on the order of picograms (10^{-12}g)). Minimum line width in the state-of-the-art PC boards in 1997 was less than 100 microns. On hybrid integrated circuits (HICs), line spacings may be less than 5 microns.[9]

Submicron dimensions of electronic circuits, high-voltage gradients, and an extremely high sensitivity to corrosion or corrosion products present a unique set of corrosion-related issues. The documented reasons for failures are discussed in greater detail below.

Environmental Contamination (Airborne Contaminants)

One of the most common reasons for electronic failure is environmental contaminants and conditions. The list of contaminants includes fine and coarse particles of such species as chlorides, sulfates, sodium, ammonium, potassium, magnesium, and calcium. The single most important environmental condition affecting the impact of particulate matter and gases (such as sulfur dioxide and nitrogen oxides) is relative humidity. Coarse particles (2.5 to 15 microns) are typically formed as a result of human activity[10] or originate from soil. Fine particles (0.1 to 2.5 microns) come from the combustion of fossil fuels and, at times, from volcanic and geological activity.

In electronic devices, coarse particles may cause malfunctions by interrupting electrical contact between mating pairs of contacts on connectors or relays. They typically require higher relative humidity conditions than the fine particles.

According to the ISA – Instrument Systems and Automation Society standard, there are four classes of industrial atmospheres with respect to copper reactivity. The summary is presented in table 3.

Table 3. Classification of industrial atmospheres' corrosivity to copper.[11]

CLASS	DESCRIPTION	EXPECTED TIME-TO-FAILURE
G1 (mild)	Corrosion is not a factor (less than 300 angstroms per month)	No corrosion-related failures
G2 (moderate)	Corrosion is measurable (less than 1,000 angstroms per month)	Failure within 3-4 years
G3 (harsh)	High probability of corrosion (less than 2,000 angstroms per month)	Failure within 1-2 years
G4 (severe)	Considerable corrosion (less than 3,000 angstroms per month)	Failure within 1 year

Another classification of the corrosivity of the environment is based on the levels of relative humidity and contaminants.

FORMS OF CORROSION

Anodic Corrosion

Given the spacing between components of the ICs, when a voltage is applied to a device, voltaic gradients on the order of 10^5 to 10^6 V/cm can exist across surfaces, accelerating electrochemical corrosion reactions and ionic migration. In ICs, positively biased aluminum metallizations are susceptible to corrosion. Combination of the electric fields, the atmospheric moisture, and the contamination by halides leads to corrosion attack on aluminum. Gold and copper metallizations are also subject to corrosion under these conditions.

Cathodic Corrosion

Negatively biased aluminum metallizations, as with those with the positive bias, can also corrode in the presence of moisture due to high (basic) pH produced by the cathodic reaction of water reduction. High pH leads to dissolution of the passive surface layer of oxides and aluminum substrate with the corresponding increases in conductor resistance (up to an open circuit).

Electrolytic Metal Migration

Detected early on in electromechanical switches, this problem occurs in relation to the silver-containing compounds. In the presence of moisture and an electric field, silver ions migrate to a cathodically (negatively) charged surface and plate out, forming dendrites. The dendrites grow and eventually bridge the gap between the contacts, causing an electric short and an arc. Even a small volume of dissolved metal can result in formation of a relatively large dendrite. Under certain humidity and voltage gradient conditions, a 30-day exposure becomes equivalent to 4 years of service in a typical office environment.[10] Other materials susceptible to the metal migration include gold, tin, lead, palladium, and copper.

Pore-Creep in Electrical Contacts and Metallic Joints

To prevent tarnishing of connectors and contacts, a noble metal (e.g., gold) is plated on the contact surface. Since the coverage is never complete, the substrate material can corrode at the imperfections. If the substrate is copper or silver, and it is exposed to a sulfur- or chloride-containing environment, corrosion products can creep out from the pores and over the gold plating, forming a layer with high contact resistance.

Fretting Corrosion of Separable Connectors With Tin Finishes

Fretting corrosion in electronic components is manifested as the continuous formation and flaking of tin oxide from a mated surface on tin-containing contacts. As the components start to utilize more and more tin (rather than gold, to cut the costs), the problem becomes more frequent. The only solution for this hard-to-diagnose, and often intermittent, problem is to replace the faulty part.

Galvanic Corrosion

Galvanic corrosion occurs when two dissimilar metals, such as aluminum and gold, are coupled together, as is commonly done for packaged (plastic encapsulated) integrated circuits. The polymers used for packaging are porous and the gaskets around hermetic covers (such as ceramic or metal) sometimes leak; therefore, in humid environments, moisture can permeate to the IC bond pad, creating conditions conducive to galvanic corrosion. Electronic devices tend to dissipate considerable heat during operation, which leads to reduced relative humidity. During power-down or storage periods, the relative humidity rises, which presents more danger.[12]

Processing-Related Corrosion of Integrated Circuits

IC circuits are exposed to a number of aggressive media used in reactive ion etching (RIE) or wet etching for patterning of aluminum lines, which can lead to corrosive residues. RIE of aluminum metallizations utilizes a combination of aggressive chlorine-containing gases. If removed untreated from the etcher, patterned structures are covered with aluminum chloride residue, which is hydroscopic and forms hydrochloric acid in the presence of moisture.[12]

<u>Micropitting on Aluminum on IC During Processing</u>

Aluminum metallizations, alloyed with copper, can form intermetallic compounds (such as Al_2Cu) along the grain boundaries, which act as cathodic sites relative to the aluminum adjacent to the grain boundaries. This leads to dissolution of an aluminum matrix in the form of micropitting during the rinsing step after chemical etching.

Corrosion of Aluminum by Chlorinated/Halogenated Solvents

Both liquid and vapor-phase halogenated solvents used for production of ICs and PCs readily corrode aluminum-containing components. Water contamination of the solvents increases the time-to-corrosion on the one hand; however, on the other hand, it increases the subsequent corrosion rate. Dilution of the stabilized solvents with aromatic or alcohol solvents leads to the breakdown of the halogenated solvent and the formation of chloride ions, which corrode aluminum and aluminum-copper alloys.

Solder Corrosion

Lead-tin solder alloy's resistance to corrosion in aqueous and gaseous environments is a function of the alloy composition. It improves significantly when the tin content increases above two weight percent. Lead forms unstable oxides, which easily react with chlorides, borates, and sulfates.(12)

Corrosion of Magnetic and Magneto-Optic Devices

Besides electronic circuits, corrosion-related failures can occur in advanced magnetic and magneto-optic storage devices, where thin-film metal discs, thin-film inductive heads, and magneto-optic layers are affected. Corrosion takes place in sites where the deposited carbon overcoat is lacking due to intentional roughening of the disc and where the magnetic cobalt-based layer and nickel-phosphorus substrate become exposed. Given the potential differences between the noble (positive) carbon and the metal substrate, a galvanic couple may form, leading to rapid galvanic-induced dissolution of the magnetic material.(12)

Magneto-optic devices utilize extremely reactive alloys for the recording media (due to high terbium content). Exposure of magneto-optic films to aqueous solutions or high-humidity conditions results in a localized attack (pitting), even during storage in ambient office conditions.(12)

While attempts have been made to mitigate corrosion of electronics by encapsulating the components in plastics, polymers are permeable to moisture. Hermetically sealed ceramic packaging is more successful; however, care must be exercised to prevent moisture and other contaminants from being sealed in. One common approach for mitigating corrosion of circuits housed inside a relatively large-size chassis includes the use of volatile inhibiting compounds (requires periodic replacement of the carrier).

CORROSION COSTS

The cost of corrosion is very difficult to determine. Arguably, in many instances, particularly in the case of consumer electronics, the devices would become technologically obsolete long before corrosion-induced failures occur. Also, while corrosion-related user costs (due to irretrievably lost data) could be staggering, as electronic information and data exchange become more and more intensive, most sensitive information is frequently backed up.

Capital-intensive industries with significant investments in durable equipment with a considerable number of electronic components (e.g., defense, airline, etc.) tend to keep the equipment for longer periods of time (tens of years), such that corrosion is likely to become an issue. There is even an opinion that the vast majority, if not all, of the electronic component failures are caused by corrosion. (13)

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