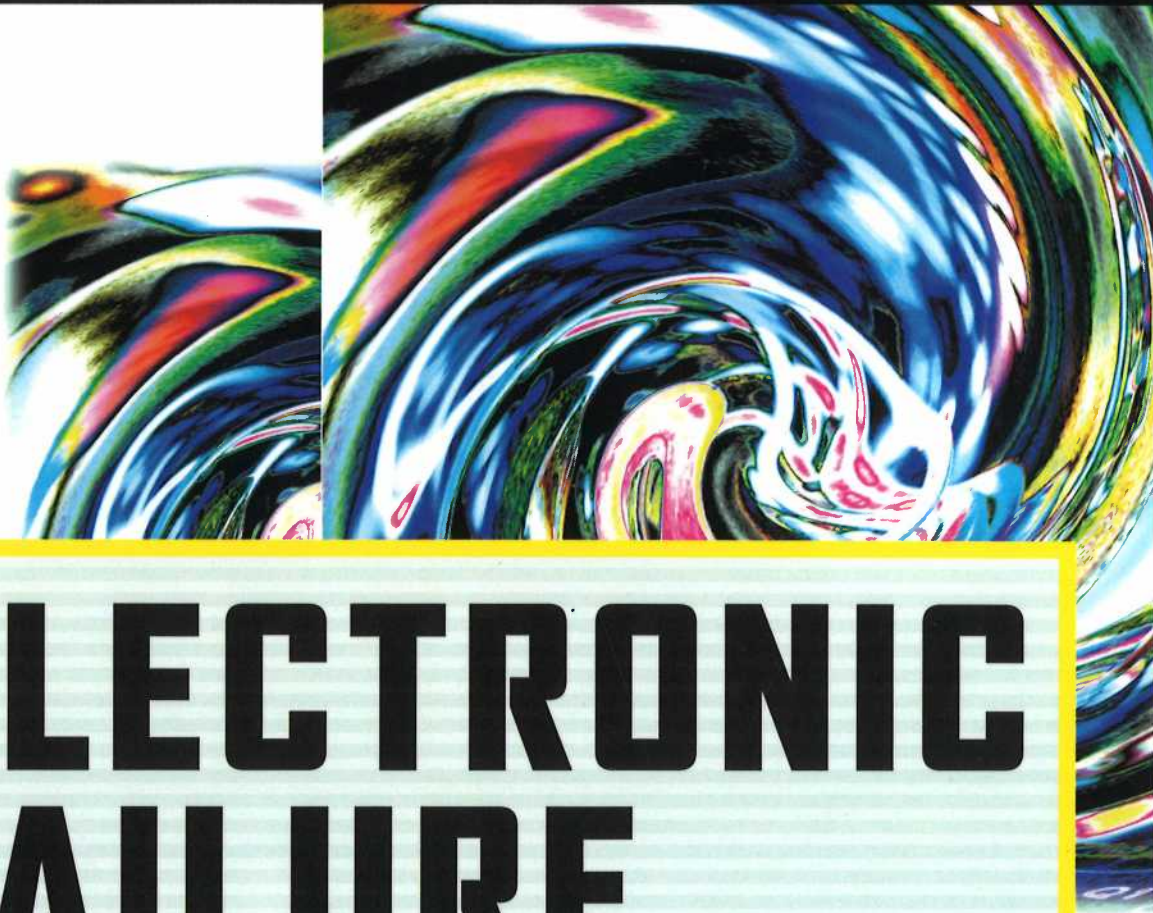


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ELECTRONIC FAILURE ANALYSIS HANDBOOK

PERRY L. MARTIN

ELECTRONIC FAILURE ANALYSIS HANDBOOK

ELECTRONIC FAILURE ANALYSIS HANDBOOK

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ELECTRONIC FAILURE ANALYSIS HANDBOOK

*Techniques and Applications for
Electronic and Electrical Packages,
Components, and Assemblies*

Perry L. Martin

National Technical Systems

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To my wife, Denise

Your support and understanding made this possible.

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PREFACE

The rapidly evolving fields of semiconductor and microelectronic failure analysis have dominated international reliability and failure analysis conferences. This is quite understandable, given that the microelectronics industry was the first to integrate failure analysis into its corporate culture. This synthesis has resulted in huge increases in microelectronic reliability over the last several decades, and this success has spawned similar activities in other electronics related industries. Electronic failure analysis (EFA) is now embodied as part of the development and manufacturing process for parts suppliers, systems/subsystems designers and fabricators, the power industry, and others. Although the application of electronic and electrical failure analysis has increased, the documentation of these nonmicroelectronic efforts has for the most part been neglected. *The Electronic Failure Analysis Handbook: Techniques and Applications for Electronic and Electrical Packages, Components, and Assemblies* is an attempt to address this broadly based and neglected audience.

Electrical and electronic failures and failure analyses occur throughout a product's life-cycle. These failures and their associated analyses become more costly as the product progresses into each successive phase of technology and market maturation. The electronics industry is learning that aggressive use of failure analysis in the early stages of a product's life-cycle can increase reliability and will increase overall net profits. Yet, some manufacturers are not quick to learn, and this creates markets for the failure analyst to provide services in the insurance and legal areas. Just as with microelectronics, these areas are addressed in the handbook but not emphasized.

I have always felt that the subject area of electronic failure analysis could easily fill out a three-volume set. Market forces constrain us to a single volume, so as editor, some tough decisions had to be made about handbook emphasis and content. For reader convenience, this handbook is divided into three parts. Part 1 is the smallest section of the handbook and deals with the utilization of electronic failure analysis. Included is an introduction to the causes of electronic failures, their distribution throughout product life, failure avoidance, quality programs, product liability, and other related issues. Part 2 deals with analysis techniques and consists of two parts. Chapters 4 through 7 describe *nondestructive* techniques, whereas Chapters 8 through 12 pertain to *destructive* techniques. The application and optimization of these techniques to electronic materials is emphasized. Part 3 is about specific electronic packaging and component technologies. To the extent possible, the reader is introduced to the manufacturing materials and processes used to produce these technologies, typical failure modes and mechanisms, applicable failure analysis techniques, and application guidelines. Many of these chapters feature failure analysis case studies.

The Electronic Failure Analysis Handbook is a comprehensive reference and guide to electronic failure analysis, and I am confident that it will be a valuable addition and companion volume to the Electronic Packaging and Interconnection Series. This handbook could not have been produced without the hard work of the many outstanding chapter authors. Each of these scientists, engineers, and technologists is a recognized expert in a particular field. Together, their offerings form an inclusive and informative study of the field of electronic failure analysis.

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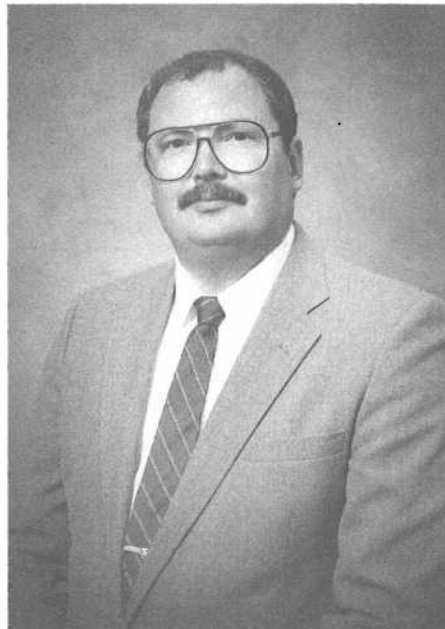
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Introduction to Electronic Failure Analysis

CHAPTER 1

OVERVIEW OF ELECTRONIC COMPONENT RELIABILITY

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1.1 INTRODUCTION

Failure analysis is the process of determining the cause of failure, collecting and analyzing data, and developing conclusions to eliminate the failure mechanism causing specific device or system failures. Failures can occur throughout a product's life cycle. These failures can result from design, workmanship, components and manufacturing processes, overstress, and maintenance. Table 1.1 generically outlines factors affecting reliability.

Table 1.1 Distribution of Factors Affecting Reliability¹

Factor	Failure percentage
Maintenance shop	17
Hardware reliability	16
Retest OK	28
Design	21
Quality	18

It is all too often that a failure analyst has limited information concerning the cause of a failure. Details surrounding the cause will not only aid the analyst in the failure analysis process, but the results of the analysis also will be more meaningful when completed. A failure reporting, analysis, and corrective action system (FRACAS), as described in Chapter 2, is used by many organizations to track failures associated with their products. A FRACAS can provide the valuable information necessary to perform a complete and accurate failure analysis. When data is not available, the analyst may take the role of a "private investigator" to determine details surrounding the cause of failure. A complete and accurate failure analysis will allow a designer or user to take the action necessary to remedy the problem. Cost savings associated with the corrective action are typically enough to pay for the failure analysis, and this savings can be multiplied many times over by eliminating future occurrences of the problem.

1.2 FAILURE TYPES

Electronic failures can be broken into basically three distinct and separate classes of failures; early-life, event-related, and wearout. Early-life failures, also known as *infant mortalities*, is the result of defects introduced during the manufacturing or assembly process.

1.1

The useful life period is characterized by a relatively constant failure rate caused by randomly occurring events. Wearout failure mechanisms occur as a result of prolonged exposure to operational or environmental stresses and will occur in the entire population of items if they are in service long enough.

Initially, an item typically exhibits a high failure rate. This failure rate decreases during the infant mortality period and stabilizes when weak and defective units have been eliminated. Failures occurring in the initial phase of deployment usually result from built-in flaws due to faulty workmanship, transportation damage or installation errors. Causes of infant-mortality failures include:

- Inadequate quality control
- Uncontrolled manufacturing processes
- Inadequate component and system test specifications
- Component and system design deficiencies
- Material deficiencies
- Improper handling and packaging
- Incorrect setup, installation, or procedures
- Incomplete testing

Infant-mortality failures can be reduced by monitoring and controlling the manufacturing process. Failure analysis is vital during this phase to identify and correct the causes of problems so they can be eliminated prior to deployment.

The useful life period is normally characterized by relatively infrequent and unpredictable failures. The specifics vary among hardware types and components and will vary based on margins used in the design of an equipment. Failures occurring during the useful life period are referred to as *random failures* because of this infrequent and unpredictable nature. That is not to say, however, that the failures do not have a specific root cause, or that the occurrence is unavoidable. These failures may be the result of component or system design deficiencies or may be induced by users or maintenance personnel. Causes of useful life failures include:

- Inadequate component or system design margins
- Misapplication
- Latent component and system defects
- Excessive electrical, thermal or physical stress (beyond design limits)

The failure rate of a component will increase rapidly in the wearout phase. Wearout failures are due primarily to the deterioration of the design strength of a device resulting from the operation and exposure to environmental fluctuations. This deterioration may result from various physical and chemical phenomena that include:

- Corrosion/oxidation
- Insulation breakdown
- Frictional wear or fatigue
- Shrinking/cracking of plastic materials
- Metal migration

Wearout failures may be reduced or eliminated through preventive maintenance and by providing adequate design margins to extend the life of components.

1.3 ENVIRONMENTAL STRESSES CAUSING ELECTRONIC COMPONENT AND SYSTEM FAILURES

The environmental stresses to which an equipment is exposed during manufacturing, operation, shipping, and storage all have an effect on reliability. During manufacture, equipment can be subjected to a variety of stresses, including temperature extremes and cycling, humidity, dust, and so on. If the manufacturing processes are not under control or were not properly designed, the reliability of the equipment will be affected. Some of the effects take the form of latent defects: defects that are not readily noticeable but are virtual "time bombs" waiting to cause a failure. The types and levels of stresses to which an equipment will be subjected in operation depend on the environment in which it is used. Stresses arise from internal and external conditions, such as vibration, shock, radiation, and weather. These conditions seldom occur sequentially or alone; combinations of these conditions present the greatest stress.

The conditions and physics relating to the failure process provide an understanding of the mechanisms that cause failure. Electronic components are susceptible to various forms of damage that can be attributed to a limited number of physical or chemical mechanisms. Primary failure mechanisms include:

- Corrosion
- Distortion
- Fatigue and fracture
- Wear

The majority of electronic component failures analyzed are often corrosion related, but other mechanisms considered mechanical in nature also influence the reliability of electronic components. It is not unusual for connections and electronic elements that receive vibration and movement to fail from fatigue or fracture. Table 1.2 provides a description and types of mechanisms affecting the reliability of electronic and electromechanical components.

Failures relating to distortion, fatigue and fracture usually occur as a result of an equipment being operated outside of its design environment or beyond its intended life. Environmental factors that accelerate failures in electronic components and assemblies include vibration, thermal cycling, and thermal shock. Table 1.3 provides the distribution of failures with respect to environmental factors found in an airborne environment.

Temperature extremes at or beyond design limits of a component or system, and at high rates of temperature cycling, can occur in the operational environment. In some cases, the equipment might be installed in a temperature-controlled compartment. In others, the equipment will be directly exposed to temperature extremes and cycling. Cold soaking for hours prior to start-up will make equipment subject to thermal shock when it is powered up. The effects of temperature extremes, cycling, and thermal shock include parameter drift, mechanical deformation, chemical reactions, increased contact resistance, dielectric breakdown, and electromigration. To address the potential problems associated with temperature extremes, cycling and thermal shock, several approaches are commonly used. The

Table 1.2 Mechanisms Affecting the Reliability of Electronic and Mechanical Components

Distortion	Fatigue and fracture	Wear	Corrosion
Buckling	Ductile fracture	Abrasive wear	Corrosion fatigue
Yielding	Brittle fracture	Adhesive wear	Stress corrosion
Creep	Fatigue fracture	Subsurface—origin fatigue	Galvanic corrosion
Creep buckling	High-cycle fatigue	Surface—origin fatigue	Crevice corrosion
Warping	Low-cycle fatigue	(pitting)	Pitting corrosion
Plastic deformation	Residual stress fracture	Subcase—origin fatigue	Biological corrosion
(permanent)	Embrittlement fracture	(spalling)	Chemical attack
Plastic deformation	Thermal fatigue fracture	Cavitation	Fretting corrosion
(temporary)	Torsional fatigue	Fretting wear	
Thermal relaxation	Fretting fatigue	Scoring	
Brinnelling			

Table 1.3 Distribution of Environmentally Related Failures in an Airborne System¹

Environmental factor	Failure percentage
Sand and dust	6
Moisture	19
Shock	2
Temperature	40
Salt	4
Altitude	2
Vibration	27

basic design can incorporate techniques to promote the even distribution of heat, thereby preventing hot spots and providing adequate cooling. Parts and components capable of operating in high temperatures can be selected. External cooling, insulation, and other design techniques reduce the periodicity and magnitude of temperature cycling and protect against thermal shock. Table 1.4 summarizes the effects, sources, and corrective actions required to eliminate the effects of temperature on components and systems.

Humidity and moisture can produce undesirable effects in electronics. It is not just those systems at sea or exposed to the weather for which moisture is a problem. Perfectly dry air is an exception. Humidity is nearly an ever-present condition, and it takes little to convert that humidity to moisture. For example, if a vehicle that has been operated in the cold outdoors is parked in a warm garage, condensation quickly occurs. Humidity can cause corrosion, electrical shorts, breakdown in insulation, and changes in resistance. Humidity can be controlled through design (hermetically sealed components, desiccants, and so on) and through environmental control systems that remove moisture. Controlling temperature changes can prevent condensation, and drains can be provided to eliminate any moisture that does condense inside equipment. Table 1.5 summarizes the effects, sources, and corrective actions required to eliminate the effects of humidity and moisture on components and systems.

Equipment located at sea or near coastal areas is subject to salt fog. Moisture and salt can combine to form a serious environmental condition. The effects on equipment reliability caused by moisture are exacerbated by the salt, which can accelerate contamination and

Table 1.4 Effects of Temperature on Components and Systems

Environment	Principal effects	Corrective action	Sources
High Temperature	▪ Acceleration of chemical reactions ▪ Deterioration of insulations ▪ Outgassing of plastic materials ▪ Reduced viscosity of lubricants ▪ Dielectric breakdown ▪ Electromigration ▪ Electrical parameter drift	▪ Minimize temperature through design and cooling ▪ Eliminate heat source or isolate it from other potentially affected components or assemblies ▪ Provide heat conduction paths	Sources of high temperature include ambient temperature, component self- heating, and friction of mechanical and electromechanical assemblies
Low Temperature	▪ Materials become brittle ▪ Viscosity of lubricants increases ▪ Water condensation ▪ Ice formation ▪ Reduced chemical reactions ▪ Shock/isolation mounts stiffen ▪ Electrical parameter changes	▪ Provide heating ▪ Insulate ▪ Incorporate materials designed for low temperatures	Typically experienced in uncontrolled environments
Thermal Cycling	▪ Stress relaxation (electrical contacts) ▪ Ductile and brittle fractures ▪ Material deformation ▪ Dielectric breakdown ▪ Electromigration ▪ Electrical parameter drift	▪ Minimize coefficient of thermal expansion (CTE) differences between materials ▪ Control or eliminate thermal cycling by introducing heating/cooling as required	Experienced in uncontrolled environments, as a result of power on/off cycling and when an equipment is cycled between two different environments during operation
Thermal Shock	▪ Material cracking ▪ Seal failures ▪ Ruptures ▪ Electrical parameter drift	▪ Minimize CTE mismatches ▪ Use appropriate mechanical design tolerances	Transition of an equipment between two temperature extremes

Table 1.5 Effects of Humidity and Moisture on Components and Systems

Environment	Principal effects	Corrective action	Sources
Humidity and moisture	- Corrosion of materials - Breakdown in insulations - Changes in resistance - Fungus growth	- Control environment - Select moisture-resistant or hermetic parts - Use conformal coatings - Provide drains to eliminate condensed moisture	Humidity is present in the natural environment. Rapid cooling of equipment can cause condensation.

corrosion of contacts, relays, and so forth. Equipment can be protected against salt fog by hermetically sealing components or by installing the equipment in environmentally controlled areas or shelters. Table 1.6 summarizes the effects, sources and corrective actions required to eliminate the effects of salt fog on components and systems.

Table 1.6 Effects of Salt Fog on Components and Systems

Environment	Principal effects	Corrective action	Sources
Salt fog	- Combines with water to form acid/alkaline solutions - Corrosion of metals - Insulation degradation	- Protective coatings - Eliminate dissimilar metals - Use hermetic seals	Salt is found in the atmosphere, the oceans, lakes, and rivers, and on ground surfaces.

Sand and dust can interfere with the mechanical components of electronic systems. Switches, relays, and connectors are vulnerable to the effects of sand and dust intrusion. Hermetically sealing components or installing equipment in environmentally controlled areas can eliminate or mitigate the effects of sand and dust. Table 1.7 summarizes the effects, sources, and corrective actions required to eliminate the effects of sand and dust.

Table 1.7 Effects of Sand and Dust on Components and Systems

Environment	Principal effects	Corrective action	Sources
Sand and Dust	- Long-term degradation of insulation - Increased contact resistance - Clogging of electromechanical components and connectors - Acids formation when moisture is present - Will collect at high static potential points and can form ionization paths	- Control environment - Incorporate protective coatings and enclosures - Filter air	Sand and dust are prevalent in all uncontrolled environments. Air turbulence and wind can force dust and sand into cracks and crevices in equipment.

Decreases, particularly rapid ones, in atmospheric pressure can cause failure in components if the design does not allow internal pressure to rapidly re-equalize. Decreases in pressure can also lead to electrical arcing, particularly in the presence of high voltage. Proper design and installation in environmentally controlled areas can avoid problems associated with pressure. Table 1.8 summarizes the effects, sources, and corrective actions required to eliminate the effects of atmospheric pressure on components and systems.

Table 1.8 Effects of High Altitude on Components and Systems

Environment	Principal effects	Corrective action	Sources
High altitude	- Induced damage due to pressure differential in a product - Evaporating/drying due to outgassing - Forms corona (arcing) - Ozone generation - Reduction of electrical breakdown voltages - Chemical changes within organic materials (e.g., rubber)	- Pressurize - Increase mechanical strength - Properly insulate high-voltage components - Minimize use of organic materials	Aircraft or other applications susceptible to rapid fluctuations in altitude or atmospheric pressure

As equipment is subjected to vibration, connections can fail, the substrates of micro-electronic parts can fracture, and work hardening can occur in mechanical components. Vibration can be caused mechanically and acoustically and is either random or sinusoidal. Through proper design, vibration effects can be avoided (avoiding resonant frequencies through stiffening, orientation, and so on) or reduced (use of vibration isolators, and so forth).

The sudden or violent application of a force to an equipment causes mechanical shock. The equipment is subjected to rapid acceleration or deceleration, and the resultant forces can destroy connections, fracture structures, and break loose particles that can contaminate electronic components that incorporate a cavity in their design. Shock can occur when a mechanic drops the equipment as it is removed for maintenance or when an aircraft makes a hard landing. External or internal shock mounting, ruggedized packaging, and other techniques can reduce the level of shock actually experienced. Table 1.9 summarizes the effects, sources, and corrective actions required to eliminate the effects of vibration and mechanical shock on components and systems.

Table 1.9 Effects of Vibration on Components and Systems

Environment	Principal effects	Corrective action	Sources
Vibration	- Intermittent electrical contacts - Touching/shorting of electrical parts - Wire chafing - Loosening of hardware - Component/material fatigue	- Stiffen mechanical structure - Reduce moment of inertia - Control resonant frequencies	Vibration isolation is the controlled mismatch of a product's resonant and natural frequencies. It does not usually provide shock isolation. Shock mounts can increase vibration damage.
Mechanical shock	- Interference between parts - Permanent deformation due to overstress	- Use stronger material (as stiff and as light as possible) - Use shock mounts - Superstructure should be stiffer than supporting structure - Use stiff supporting structure if system natural frequency is >35 Hz - Transmit rather than absorb energy	The sudden application of force, measured in Gs of acceleration and milliseconds duration. Can be caused by handling, transportation, gunfire, explosion and/or propulsion.

The effects of solar radiation can be a significant thermal load beyond any load from the local ambient environment. This is especially true for automobiles and aircraft on runways. Sheltering and the use of different types of paint can help. Wind loading can be a significant stress, especially on large structures such as antennas.

Associated with electrical and electronic equipment are electrical and magnetic fields and emanations. These fields and emissions may be intentional (radio transmissions, for example) or unintentional (due either to poor design or to unavoidable laws of physics). The fields and emanations of two pieces of equipment can interfere (hence, the term *electromagnetic interference* or EMI) with the proper operation of each. Proper design is, of course, the best and first step in avoiding EMI problems. Shielding, grounding, and other techniques can also reduce EMI.

1.4 OTHER FACTORS INFLUENCING ELECTRONIC FAILURES

The manufacturing and maintenance environment can also affect the reliability of electronic components. Many of the failures reviewed by a failure analyst are a result of manufacturing errors. Table 1.10 outlines manufacturing defects typically uncovered during the manufacturing process.

Table 1.10 Manufacturing Defects
Uncovered during the Manufacturing
Process¹²

Manufacturing defect	Percentage
Open	34
Solder bridges	15
Missing parts	15
Misoriented parts	9
Marginal joints	9
Balls, voids	7
Bad parts	7
Wrong parts	7

Static electricity is also a serious threat to modern electronic devices and is prevalent in areas of low humidity. Electrostatic discharge (ESD) can degrade the operation of a component, cause component failures, or go undetected and result in latent defects. Certain devices are inherently more vulnerable to ESD damage. Parts should be selected with an eye toward ESD susceptibility. Electrostatic discharge susceptibility test and classification data on electronic components can be found in Ref. 15.

Precautions should be taken to reduce sources of electrostatic charges. Electrostatic charges can be brought into the assembly, repair, and part storage areas by people. They can also be generated in these areas by normal work movements. Clothing articles of common plastic such as cigarette and candy wrappers, styrofoam cups, part trays and bins, tool handles, packing containers, highly finished surfaces, waxed floors, work surfaces, chairs, processing machinery, and many other prime sources of static charges. These electronic charges can be great enough to damage or cause the malfunction of modern electronic parts, assemblies, and equipment.

Electrostatic discharge can cause intermittent upset failures, as well as hard catastrophic failures, of electronic equipment. Intermittent or upset failures of digital equipment are usually characterized by a loss of information or temporary disruption of a function or functions. In this case, no apparent hardware damage occurs, and proper operation may be resumed after the ESD exposure. Upset transients are frequently the result of an ESD spark in the vicinity of the equipment.

While upset failures occur when the equipment is in operation, catastrophic or hard failures can occur at any time. Most ESD damage to semiconductor devices, assemblies, and electronic components occurs below the human sensitivity level of approximately 4000 V. Other failures may not be catastrophic but may result in a slight degradation of key electrical parameters such as (a) increased leakage current, (b) lower reverse breakdown voltages of P-N junctions or (c) softening of the knee of the V-I curve of P-N junctions in the forward direction. Some ESD part damage is more subtle. It can remain latent until additional operating stresses cause further degradation and, ultimately, catastrophic failure. For example, an ESD overstress can produce a dielectric breakdown of a self-healing nature. When this occurs, the part can retest good, but it may contain a weakened area or a hole in the gate oxide. During operation, metal may eventually migrate through the puncture, resulting in a direct short through the oxide layer.

The natural environment in which maintenance occurs is often harsh and can expose equipment to conditions not experienced during normal operation. Maintenance itself can involve the disconnection and removal of equipment and subsequent reinstallation and reconnection of equipment. This "remove and reinstall" process is not always done because the equipment has failed. Often, equipment may be removed for test and calibration or to allow access to another failed item. This secondary handling (the primary handling required when the equipment has failed) and the natural environment make up the maintenance environment. The maintenance environment can degrade the reliability of equipment not properly designed for it. Maintenance-induced failures can be a significant factor in the achieved field reliability of an item. Proper design can mitigate both the probability and consequences of maintenance-induced failure.

Rain, ice, and snow can affect the temperature of equipment and can introduce moisture, with all its associated problems. These weather elements are a particular problem when maintenance is performed. During maintenance, access doors and panels are opened, exposing even those equipments located in environmentally controlled areas. Proper packaging, the use of covers or shrouds, and other techniques can be used to protect equipment from the elements. Internal drains, sealants and gaskets, and other design measures can also be used to protect equipment.

Equipment must be capable of surviving the rigors of being shipped via all modes of transport over intercontinental distances. The process of preparing for shipment, the shipment itself, the process of readying the equipment for use after delivery, and the handling associated with all these steps impose stresses sometimes more severe than the operating environment itself.

1.5 ELECTRONIC COMPONENT FAILURE MODES AND MECHANISMS

When designing systems containing electronic components, it is valuable to an engineer to have the knowledge of component failure modes and mechanisms and their probability of occurrence. These factors are also invaluable to an analyst when performing failure analyses and developing recommendations to eliminate the future occurrence of failures. Table

1.11 presents failure modes and mechanisms for a representative group of electronic components. The data used to prepare this table was collected by the Reliability Analysis Center in Rome, NY. Detailed failure distributions and specific source details are described in Ref. 11.

1.6 DORMANCY-RELATED FAILURE MECHANISMS

An area often overlooked is the affects of dormancy on electronic equipment. Dormancy can be important in the design of a product, since a predominant portion of its life cycle may be in a nonoperational mode. Moisture is probably the single most important factor affecting long-term nonoperating reliability. All possible steps should be taken to eliminate moisture from electronic devices and products. Hygroscopic materials should be avoided or protected against accumulation of excess moisture. Most failures that occur during nonoperating periods are of the same basic kind as those found in the operating mode, although they are precipitated at a slower rate. Dormancy failures may be related to manufacturing defects, corrosion, and mechanical fracture. When designing for dormancy, materials sensitive to cold flow and creep, as well as metallized and nonmetallic finishes that have flaking characteristics, should be avoided. Also, the use of lubricants should be avoided. If required, use dry lubricants such as graphite. Teflon® gaskets should not be used. Conventional rubber gaskets or silicone-based rubber gaskets are typically preferable.

When selecting components, it is recommended that only components with histories of demonstrated successful aging be used. Semiconductors and microcircuits that contain deposited resistors may exhibit aging effects. Parts that use monometallization are recommended to avoid galvanic corrosion. Chlorine or other halogen-containing materials should not be sealed within any circuitry components. Variable resistors, capacitors, inductors, potentiometers, and electromechanical relays are susceptible to failure in dormant environments and are generally not recommended.

It is recommended that components and systems in storage should not be periodically tested. Historical data shows that failures are introduced as a result of the testing process. Causes of many of the failures were test procedures, test equipment, and operator errors. Storage guidelines are:

- Disconnect all power.
- Ground all units and components.
- Pressurize all coax waveguides (use nitrogen to prevent moisture and corrosion).
- Maintain temperature at $50^{\circ}\text{F} \pm 5^{\circ}\text{F}$ ($10^{\circ}\text{C} \pm 2.7^{\circ}\text{C}$) (drain all equipment of water to prevent freezing or broken pipes).
- Control relative humidity to 50°F (10°C) ± 5 percent (reduces corrosion and prevents electrostatic discharge failure).
- Periodically recharge batteries.
- Protect against rodents: squirrels have chewed cables, mice have nested in electronic cabinets and porcupines have destroyed support structures (wood). Door/window seals, traps/poison, and frequent inspection protect against these rodents.

Failure mechanisms, failure modes and accelerating factors of electronic components subjected to periods of dormancy are described in Table 1.12.

Table 1.11 Failure Mode Distributions^{1, 11}

Device type	Failure mode	a*	Device type	Failure mode	a*
Alarm, annunciator	False indication	.48	Battery, lead acid	Degraded output	.70
	Failure to operate on demand	.29		Short	.20
	Spurious operation	.18		Intermittent output	.10
	Degraded alarm	.05	Battery, rechargeable, Ni-Cd	Degraded output	.72
Battery, lithium	Degraded output	.78		No output	.28
	Start-up delay	.14			
	Short	.06			
	Open	.02	Capacitor, paper	Short	.63
Capacitor, aluminum, electrolytic, foil	Short	.53		Open	.37
	Open	.35			
	Electrolyte leak	.10	Capacitor, mica/glass	Short	.72
	Decrease in capacitance	.02		Change in value	.15
Capacitor, ceramic	Short	.49		Open	.13
	Change in value	.29	Capacitor, tantalum	Short	.57
	Open	.22		Open	.32
Capacitor, plastic	Open	.42		Change in value	.11
	Short	.40	Capacitor, variable, piston	Change in value	.60
	Change in value	.18		Short	.30
Capacitor, tantalum, electrolytic	Short	.69		Open	.10
	Open	.17	Connector/connection	Open	.61
	Change in value	.14		Poor contact/intermittent	.23
Coil	Short	.42		Short	.16
	Open	.42	Crystal, quartz	Open	.89
	Change in value	.16		No oscillation	.11
Circuit breaker	Opens without stimuli	.51	Diode, rectifier	Short	.51
	Does not open	.49		Open	.29
Diode, general	Short	.49		Parameter change	.20
	Open	.36	Diode, small signal	Parameter change	.58
	Parameter change	.15		Open	.24
Diode, silicon control rectifier (SCR)	Short	.98		Short	.18
	Open	.02	Diode, thyristor	Failed off	.45
Diode, Triac	Failed off	.90		Short	.40
	Failed on	.10		Open	.10
				Failed on	.05
Diode, zener, voltage reference	Parameter change	.69	Diode, zener, voltage regulator	Open	.45
	Open	.18		Parameter change	.35
	Short	.13		Short	.20
Electric motor, ac	Winding failure	.31	Fuse	Fails to open	.49
	Bearing failure	.28		Slow to open	.43
	Fails to run, after start	.23		Premature open	.08
	Fails to start	.18			

Table 1.11 Failure Mode Distributions^{1, 11} (continued)

Device type	Failure mode	a*	Device type	Failure mode	a*
Hybrid Device	Open circuit	.51	Keyboard Assembly	Spring failure	.32
	Degraded output	.26		Contact failure	.30
	Short circuit	.17		Connection failure	.30
	No output	.06		Lock-up	.08
Liquid crystal display	Dim rows	.39	Meter	Faulty indication	.51
	Blank display	.22		Unable to adjust	.23
	Flickering rows	.20		Open	.14
	Missing elements	.19		No Indication	.12
Microcircuit, digital, bipolar	Output stuck high	.28	Microcircuit, digital, MOS	Input open	.36
	Output stuck low	.28		Output open	.36
	Input open	.22		Supply open	.12
	Output open	.22		Output stuck low	.09
Microcircuit, interface				Output stuck high	.08
	Output stuck low	.58	Microcircuit, linear	Improper output	.77
	Output open	.16		No output	.23
	Input open	.16	Microcircuit, memory, MOS	Data bit loss	.34
	Supply open	.10		Short	.26
Microcircuit, memory, bipolar	Slow data transfer	.79		Open	.23
	Data bit loss	.21		Slow data transfer	.17
Microwave amplifier	No output	.90	Microwave attenuator	Attenuation increase	.90
	Limited voltage gain	.10		Insertion loss	.10
Microwave connector	High insertion loss	.80	Microwave detector	Power loss	.90
	Open	.20		No output	.10
Microwave, diode	Open	.60	Microwave filter	Center frequency drift	.80
	Parameter change	.28		No output	.20
	Short	.12	Microwave modulator	Power loss	.90
Microwave mixer	Power decrease	.90		No output	.10
	Loss of intermediate frequency	.10	Microwave voltage-controlled oscillator (VCO)	No output	.80
Microwave oscillator	No output	.80		Untuned frequency	.15
	Untuned frequency	.10		Reduced power	.05
	Reduced power	.10	Microwave polarizer	Change in polarization	1.00
Microwave phase shifter	Incorrect output	.90			
	No output	.10	Optoelectronic LED	Open	.70
Microwave yttrium from garnet (YIG) resonator	No output	.80		Short	.30
	Untuned frequency	.15	Power Supply	No Output	.52
	Reduced power	.05		Incorrect Output	.48
Optoelectronic sensor	Short	.50			
	Open	.50			

Table 1.11 Failure Mode Distributions^{1, 11} (continued)

Device type	Failure mode	a*	Device type	Failure mode	a*
Printed wiring assembly	Open	.76	Relay	Fails to trip	.55
	Short	.24		Spurious trip	.26
				Short	.19
Resistor, composition	Parameter change	.66	Resistor, fixed	Open	.84
	Open	.31		Parameter change	.11
	Short	.03		Short	.05
Resistor, fixed, film	Open	.59	Resistor, fixed, Wirewound	Open	.65
	Parameter change	.36		Parameter change	.26
	Short	.05		Short	.09
Resistor, network	Open	.92	Resistor, thermistor	Open	.63
	Short	.08		Parameter change	.22
				Short	.15
Resistor, variable	Open	.53	Rotary switch	Improper output	.53
	Erratic output	.40		Contact failure	.47
	Short	.07			
Sensor	Erratic output	.59	Solenoid	Short	.52
	Short	.20		Slow movement	.43
	Open	.12		Open	.05
	No output	.10			
Switch, push-button	Open	.60	Switch, thermal	Parameter change	.63
	Sticking	.33		Open	.27
	Short	.07		No control	.08
				Short	.02
Switch, toggle	Open	.65	Synchro	Winding failure	.45
	Sticking	.19		Bearing failure	.33
	Short	.16		Brush failure	.22
Transducer, sensor	Out of tolerance	.68	Transformer	Open	.42
	False response	.15		Short	.42
	Open	.12		Parameter change	.16
	Short	.05			
Transistor, bipolar	Short	.73	Transistor, FET	Short	.51
	Open	.27		Output low	.22
				Parameter change	.17
				Open	.05
				Output high	.05
Transistor, GaAs FET	Open	.61	Transistor, RF	Parameter change	.50
	Short	.26		Short	.40
	Parameter change	.13		Open	.10
Tube, electron	Change in parameter	.53	Tube, traveling wave	Reduced output power	.71
	Open	.25		High helix current	.11
	Unstable output	.15		Gun failure	.09
	Short	.07		Open helix	.09

*a = failure mode probability

Table 1.12 Dormant Part Failure Mechanisms¹

Type	Mechanism	Percent failure mode	Accelerating factor
Microcircuit	Surface anomalies	35-70 Degradation	Moisture, temperature
	Wire bond	10-20 Open	Vibration
	Seal defects	10-30 Degradation	Shock, vibration
Transistor	Header defects	10-30 Drift	Shock, vibration
	Contamination	10-50 Degradation	Moisture, temperature
	Corrosion	15-25 Drift	Moisture, temperature
Diode	Corrosion	20-40 Intermittent	Moisture, temperature
	Lead/die contact	15-35 Open	Shock, vibration
	Header bond	15-35 Drift	Shock, vibration
Resistor	Corrosion	30-50 Drift	Moisture, temperature
	Film defects	15-25 Drift	Moisture, temperature
	Lead defects	10-20 Open	Shock, vibration
Capacitor	Connection	10-30 Open	Temperature, vibration
	Corrosion	25-45 Drift	Moisture, temperature
	Mechanical	20-40 Short	Shock, vibration
RF coil	Lead stress	20-40 Open	Shock, vibration
	Insulation	40-65 Drift	Moisture, temperature
Transformer	Insulation	40-80 Short	Moisture, temperature
Relay	Contact resistance	30-40 Open	Moisture, temperature
	Contact corrosion	40-65 Drift	Moisture

1.7 DETERMINING THE CAUSE OF ELECTRONIC FAILURES

The course of action taken to determine the cause(s) of an electronic failure depends on the item to be evaluated (e.g., power supply, populated printed wiring board/module or discrete piece part). The process is outlined in Figure 1.1. This process can be applied to analyze either a component or printed wiring assembly. The problem analysis path for a discrete component incorporates an external visual examination and electrical test verification. The evaluation of a printed wiring assembly is a more complex procedure, requiring fault analysis to isolate a problem. This isolation often includes the review and evaluation of manufacturing and assembly processes, board materials and construction, component mounting techniques, and connectors. Board-level electrical testing is typically the first procedure used to localize the problem. Also, it is important that the failure analyst interface with the original equipment manufacturer (OEM), since it is important that diagnostic and corrective action interchange, as well as to provide an unbiased review of results.

Higher-level assemblies may require the use of circuit analysis techniques and methods (e.g., SPICE, Monte Carlo simulation) to isolate design problems. These procedures can either provide basic information concerning the sensitivity of a circuit to variability (deg-

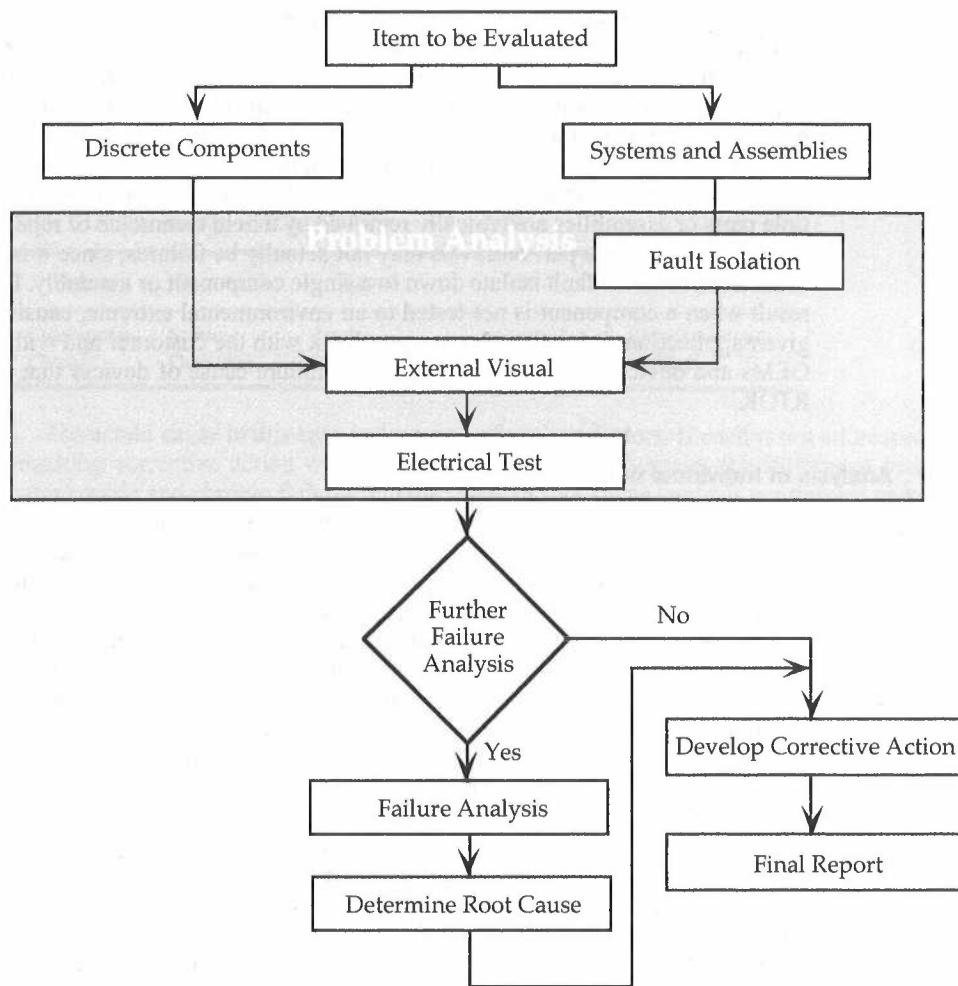


FIGURE 1.1 Electronic Problem Analysis Process Flow

radation) in the parameters of its component parts or use actual parameter variability data to simulate real-life situations and determine the probability of whether circuit performance is within tolerance specifications. In addition to providing information on the sensitivity of a circuit to degradation failures, these techniques are capable of giving stress-level information of the type needed to identify overstressed parts. Catastrophic failures can often be related to excessive environmental conditions, lack of design margin, or over-stress, which can provide valuable insight for corrective actions. These techniques will, therefore, be used to identify problems resulting from circuit designs that are not robust enough to tolerate the specific conditions being encountered.

Finite element analysis (FEA), a graphically oriented, automated technique for analyzing the effects of mechanical loads and thermal stress on a component or system, may also be utilized. It is a powerful method for modeling structures and assemblies with various

levels of mechanical, vibration, and thermal stress, and producing visual evidence of any resulting deformation, harmonic resonance, or thermal flow and induced stress patterns.

In contrast to design-related problems, failures can also be due to defective parts. A background investigation is typically conducted to determine if similar problems have been encountered, and whether they are vendor, technology, or batch related. Such investigations on previous findings can often lead to quick solutions.

Special emphasis should be given to parts and assemblies that *retest OK* (RTOK). Multiple parts or assemblies are typically removed by a field technician or repair shop during a repair. Some of these part removals may not actually be failures, since it is typically more cost effective not to fault isolate down to a single component or assembly. RTOKs can also result when a component is not tested to an environmental extreme, causing it to fail in a given application. It is often necessary to work with the customer and with the equipment OEMs and device vendor(s) to ascertain the failure cause of devices that are found to be RTOK.

1.7.1 Analysis of Individual Items

The failure analysis process incorporates reliability to identify failure mechanisms for parts and materials. A failure analyst must go beyond the symptomatic defect identified during the failure analysis process and identify and correct the basic underlying part or process problem causing the problem (e.g., the root cause).

Once a discrete part or process step (product or fabrication) causing a problem has been fault isolated, a number of sophisticated failure analysis techniques may be required to correctly determine solutions to a problem. The specific techniques required to analyze a part or process depend on the problem under study.

When performing or selecting a source for failure analysis, it may be difficult for one laboratory to have the expertise in all failure analysis techniques required to perform an analysis. A given laboratory will often have their own area of expertise. The selection of a failure analysis laboratory needs to be based on the component type and the failure analysis techniques/methods that may be required to perform the analysis. In some instances, the original vendor will perform electrical testing of devices manufactured by them. Vendors and manufacturers are usually willing to analyze their own items at no cost just to determine how well these items function in the field. Additionally, participation by company engineers in the failure analysis process can be beneficial. Experience has shown that knowledge of the circumstances of the problem under study is necessary during the performance of a failure analysis. The elimination of this step has typically led to extraneous testing or the failure to perform key testing, resulting in a requirement for additional follow-up analyses. Also, a review of this step will remove any suspicion that results have been biased by a testing facility.

1.7.2 Failure Prevention and Elimination

With the increasing emphasis on identifying the source of a problem to ensure that the failure mode is eliminated, the failure analysis definition can be expanded to include failure prevention. Additionally, reliability physics practices can be used to verify the adequacy of a process or component in satisfying its desired application early in the design process. Root cause analysis, properly applied, can identify corrective action for many problems (i.e., a failed semiconductor device, a poor yield machining operation, and a nonrobust process).

Determining corrective actions for identified problems should address both catastrophic and chronic failures and defects, as illustrated in Table 1.13. A catastrophic example would be a change of flux in a standard soldering process. The result could be poor adhesion of component leads to printed wiring board contact pads. Usually, in cases like this, the cause and effect are easily identified, and corrective action determination is straightforward. In the chronic case, yield is usually considered acceptable.

Table 1.13 Catastrophic and Chronic Failures and Defects

Failure	Occurrence	Cause	Yield	Solution
Catastrophic	Sudden	Single	Unacceptable	Straightforward
Chronic	Over time	Compound	Acceptable	Difficult

The actual cause in this case is the result of various factors. If each is not addressed, the resulting corrective action will not suffice. Figure 1.2 illustrates the difference between catastrophic and chronic failures and the result of root cause analysis continuous improvement.

The traditional "quality control" scenario of an approach to improvement is illustrated in Table 1.14. In most cases, chronic defects are either not identified or are considered to be in the "noise level" and not addressed. However, to achieve high yields, low costs, and customer satisfaction, continuous improvement, through minimization of chronic defects, must occur, as illustrated in Fig. 1.3. Improvement starts with Pareto analysis, but chronic defects may not be eliminated, because the defect factor selection is arbitrary and not thorough.

An approach to the reduction of chronic defects is illustrated in Table 1.15. The process used is PM Analysis. This approach is described in the Japan Institute of Plant Maintenance PM Analysis Cause training course. "P" stands for phenomenon and physical, and "M" stands for mechanism, machine, man, material, and method. Basically, this is a much

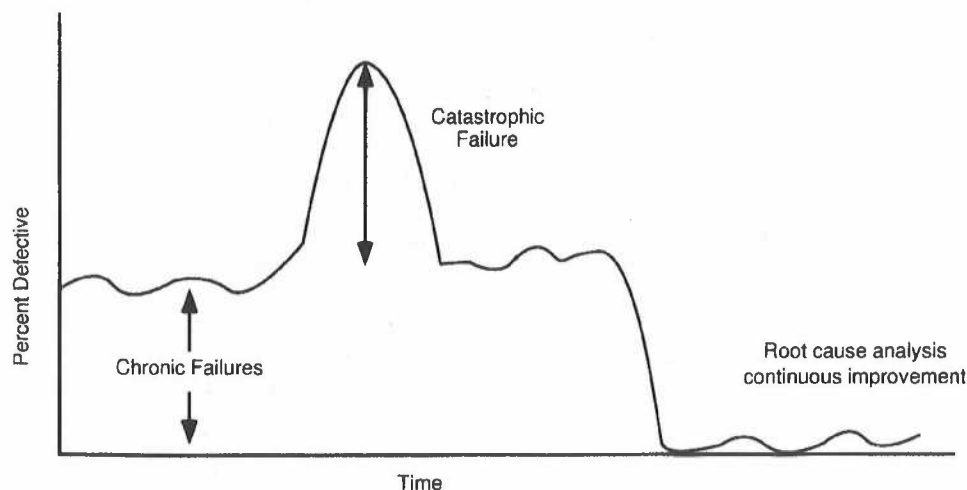


FIGURE 1.2 Difference between Catastrophic and Chronic Failures¹

Table 1.14 Traditional Approach to Improvement

Steps	Description
1. Goal	▪ Defect reduction
2. Philosophy	▪ Prioritize ▪ Analyze by priority ▪ Identify problem factors and take corrective action
3. Approach	▪ Fishbone diagram (brainstorming)
4. Success	▪ Good for catastrophic problems

Table 1.15 Improvement Approach for Achieving "Zero" Defects

Steps	Description
1. Goal	▪ Zero defects
2. Philosophy	▪ Minimize prioritization ▪ Maximize determination of defect factors ▪ Investigate each factor ▪ Correct all identified problems ▪ Attempt to correct all defect factors ▪ If not successful, change factor selection
3. Approach	▪ PM* analysis
4. Success	▪ Chronic defects

* P = phenomenon and physical; M = mechanism, machine, man, material, and method

more detailed analysis that attempts to detail all defect factors and tries to correct them to minimize chronic defects. It is important that you do not focus on only important items but also include those whose contribution is minor.

A successful continuous improvement plan would be first to apply the conventional quality control approach. If satisfactory results do not occur, then implement the more rigorous PM approach. However, it must be noted that cost and schedule factors can minimize the success of either approach. As improvements are made and yields rise, management support to continue analysis may decrease.

When the root cause of a failure has been determined, a suitable corrective action should be developed which will prevent further recurrence of this failure. Examples of corrective actions include, but are not limited to, changes in design, part derating, test procedures, manufacturing techniques, materials, and packaging.

After a corrective action has been proposed, its effectiveness should be established prior to its universal application. This may be performed on a prototype equipment, on the failed unit, in the engineering laboratory, or by various other appropriate means.

Failure analysis of items is necessary when prior problem analysis/fault isolation does not define the cause of a specific problem. It will also be used to verify problems uncovered by the fault isolation process. The following describes the capability, techniques, and expertise available to perform these failure analyses.

1.7.3 Analysis Techniques

Once the discrete part causing the problem has been fault isolated, a number of sophisticated failure analysis techniques may be required in order to correctly determine solutions for the problem. The specific technique required to analyze a part depends on the problem under study. The first step is to inspect the part using optical microscopy. This is a simple but effective method of isolating certain problems. Many of the problems whose root causes are vibration can be detected in this manner. Broken leads on an electronics board subjected to high vibration can be isolated at this level of analysis. Massive electrical overstress, packaging integrity, and external corrosion defects can also be detected using visual inspection.

The next step is to run electrical tests. This is to categorize the problem so that further analysis can be channeled most efficiently. Test sets, curve tracers, and point-to-point resistance measurements can be used at this step to determine into which of the following categories the part would fall.

1. A marginal or degradation problem, where parts coming from the tails of a normal product distribution combine to cause malfunctions.
2. A "sport," where a part falls well outside of normal product distribution, or a particular critical parameter was never specified.
3. An environmental problem, where the equipment is stressed electrically, mechanically, thermally or chemically (intentionally or unintentionally) beyond the design limit.
4. RTOK, which could result from misapplication of a part, an intermittent problem such as cracked solder or loose particles, improper removal (troubleshooting printed wiring assemblies usually cannot isolate to a single part), poor electrical connections external to the part, or software problems in the printed wiring assembly tests.

Based on experience, most of the parts fall into the last two categories listed above. Typically, over one-third of the problems can be isolated during the first two steps. The test sequence followed for analyzing the remaining two-thirds of the parts can take many different paths based on the findings during the first two steps. In any event, benign tests that do not cause irreversible changes in the part should always be used first. Depending on the findings at this point, they could include such tests as X-ray, fine and gross leak, loose particle detection (PIND), shock, vibration, centrifuge, thermal cycling, and dew point.

For hermetic cavity devices, residual gas analysis (RGA) should be run on some samples prior to opening. The analysis of the gaseous materials in the part cavity can often lead to the root causes of a problem or the forming of hypotheses that lead to solutions. This is particularly true if polymeric materials are used. RGA is also useful for package integrity, surface contamination, and metal plating problems. Immediately after the part is punctured for the RGA, a piece of tape should be placed over the hole for loose particle recovery.

If no cause is found after all nondestructive evaluation has been completed, then the destructive analysis begins. Again, the order of analysis must be carefully planned so that the maximum information can be obtained before each irreversible step is completed. Careful, detailed internal visual examination and photographic documentation is the most effective method for either solving the problem or deciding which analysis technique to use next. Often, the path of the overstress in a printed wiring assembly can be determined, as well as approximate current/voltage levels and whether the source was high or low

impedance. Good parts can then be stressed to see if the field failures can be duplicated. Visual inspection can also provide information on contamination, poor electrical interconnections, conductive and nonconductive films, adhesive failures, and manufacturing and handling defects. At this point in the analysis, experience shows that about two-thirds of the part failure causes have been isolated to the point where corrective action can be initiated.

For the remaining one-third of the parts, many techniques may be used. These are selected based on information gathered by the previous analyses. Section II, Electronic Failure Analysis Techniques, details techniques used in the failure analysis process.

1.7.4 Development of Recommended Corrective Actions

Failure and engineering analyses will identify root causes for critical part or system deficiencies. Evidence of electrostatic discharge (ESD), software, maintenance, or handling induced failures may also be uncovered. To eliminate these problems, a corrective action recommendation is required. Based on results from prior analyses, and with assistance as required from the customer, the contractor and analyst should develop corrective action recommendations. These recommendations, when implemented on the equipment early in its life cycle, will reduce maintenance cost and improve the operational readiness of the equipment.

A report describing the corrective action recommendation as it pertains to a particular component/printed wiring assembly, system application, manufacturing process, device technology, and so on will be delivered to the customer for each problem studied. This report will include a description of the problem, a summary of failure circumstance information, results of failure testing, references to other test reports and source documents, corrective action recommendations, and a cost/benefit analysis to support the action recommendations, where applicable. Corrective actions will be implemented, as appropriate, by the customer with assistance from the contractor.

1.7.5 Failure Analysis Report

A written report of the failure analysis results documents the conclusions for all concerned parties and provides a permanent record to support historical failure tracking and corrective action verification. The report should include short statements of results supported by electrical test data (where appropriate), pictures and analysis actions taken to clearly identify the failure mechanisms. Clearly stated conclusions are preferred in a bullet format. The report should include the following, as a minimum:

- Background discussion
- Item/process description
- Analyses performance
- Graphic data
- Conclusions
- Recommendations
- References

1.8 STATISTICAL DISTRIBUTIONS

Statistics are typically used in the failure analysis process to analyze data pertaining to conditions surrounding a specific failure or group of failures. Statistics are of particular importance when modeling the time-to-failure characteristics of a component or system. Several distributions typically used for this purpose include the exponential, Weibull, normal, lognormal, and gamma. The exponential distribution is probably most often used because of its simplicity, and it has been shown in many cases to fit the time-to-failure characteristics of electronic devices. This distribution, however, is not always representative of specific failure causes, and other distributions are required to model the data. A description of distributions typically used to model electronic and electromechanical component time-to-failure characteristics are provided in this section. Discrete distributions such as the binomial and poisson are not covered but are described in numerous statistics and reliability texts.

1.8.1 Exponential Distribution

The exponential distribution is widely used to model electronic reliability failures during the useful life period, which tends to exhibit random failures and a constant failure or hazard rate. The probability density function for an exponentially distributed time-to-failure random variable, t , is given by:

$$f(t) = \lambda e^{-\lambda t}$$

where λ is the failure rate and $t > 0$. The reciprocal of the failure rate is the mean expected life, and it also referred to as the *mean time between failure* (MTBF).

1.8.2 Weibull Distribution

The Weibull distribution is very versatile and can be used to represent many different time to failure characteristics. It continues to gain popularity, particularly in the area of mechanical reliability, due to this versatility. The underlying physical phenomena causing the failure, however, must be clearly understood prior to the selection of this distribution. The two-parameter Weibull probability density function in terms of time, t , is represented by the following equation:

$$f(t) = \frac{\beta}{\eta} t^{\beta-1} \exp\left[-\left(\frac{t}{\eta}\right)^{\beta}\right] \quad (\text{for } t \geq 0)$$

$$f(t) = 0 \quad (\text{for } t < 0)$$

where β is the shape parameter and η is the scale parameter, or characteristic life. When $\beta = 1$, the distribution is equivalent to the exponential distribution, and when $\beta = 3.44$, the distribution approximates a normal distribution.

1.8.3 Normal Distribution

The normal distribution is often used to model the distribution of chemical, physical, mechanical, or electrical properties of components or systems. Data conforming to a normal distribution is symmetrical about the mean of this distribution. When a value is sub-

ject to many sources of variation, irrespective of how the variations are distributed, the resultant composite of these variations has been shown to approach a normal distribution. The normal distribution is rarely used to model the time to failure of wearout mechanisms, but it can be used to model component design variations—for example, the tensile strength of materials. The probability density function is given by:

$$f(x) = \frac{1}{\sigma(2\pi)^{1/2}} \exp\left[-\frac{1}{2}\left(\frac{x-\mu}{\sigma}\right)^2\right]$$

where μ is the location parameter (which is equivalent to the mean), and σ is the scale parameter (which is equal to the standard deviation).

1.8.4 Lognormal Distribution

The lognormal distribution is a skewed distribution that can be used to model data where a large number of occurrences being measured are concentrated in the tail end of the data range. It is not as versatile as the Weibull distribution but has been shown to be applicable to the modeling of many wearout phenomena. The probability density function for the lognormal distribution is represented by:

$$f(x) = \frac{1}{\sigma x(2\pi)^{1/2}} \exp\left[-\frac{1}{2}\left(\frac{\ln x - \mu}{\sigma}\right)^2\right] \quad (\text{for } x \geq 0)$$

$$f(x) = 0 \quad (\text{for } x < 0)$$

Where μ and σ are, respectively, the mean and standard deviation of the data. The lognormal distribution is often used to describe the time-to-failure characteristics of electronic component failure mechanisms such as electromigration and time-dependent dielectric breakdown.

1.8.5 Gamma Distribution

The gamma distribution is used to model situations where a number of failure events must occur before the failure of the item of concern. The probability density function is:

$$f(x) = \frac{\lambda}{\Gamma(a)} (\lambda x)^{a-1} \exp(-\lambda x) \quad (\text{for } x \geq 0)$$

$$f(x) = 0 \quad (\text{for } x < 0)$$

where λ is the failure rate of a complete failure and a is the number of events required to cause a complete failure. $\Gamma(a)$ is the gamma function, which is represented by:

$$\Gamma[a] = \int_0^{\infty} x^{a-1} \exp(-x) dx$$

When $a = 1$, the gamma distribution is equivalent to the exponential distribution.

1.8.6 Choosing a Distribution

The specific statistical distribution best suited for a particular analysis can be determined empirically, theoretically, or by a combination of both approaches. A distribution chosen empirically is done by fitting data to a distribution using probability paper or computer software programs. Goodness-of-fit tests, such as the chi-square and Kolmogorov-Smirnov, can also be used to determine when a particular data set fits a distribution. A description of typical goodness-of-fit tests has been provided in this section.

Chi-Square Test. The chi-square test can be used to determine how well theoretical or sample data fits a particular distribution. A measure of the discrepancy between observed and expected values of a distribution is supplied by the chi-square (χ^2) statistic. The test is derived from the number of observations expected to fall into each interval when the correct distribution is chosen. The statistic is evaluated by subtracting an expected frequency from an observed frequency and is represented by:

$$\chi^2 = \sum_{j=1}^k \frac{(o_j - e_j)^2}{e_j}$$

where χ = number of events
 o = observed frequency
 e = expected frequency

Chi-square distribution tables are required to compare the value of to a critical value with the appropriate degrees of freedom. When data is limited, e.g., less than five observations from three or fewer groups or classes of data, it is recommended that a different test, such as the Kolmogorov-Smirnov (K-S) goodness-of-fit test be used.

Kolmogorov-Smirnov (K-S) Test. The Kolmogorov-Smirnov test is a nonparametric test that directly compares an observed cumulative distribution function (c.d.f.) to the c.d.f. of a theoretical or expected distribution. This test is easier to use than the chi-square test previously discussed and can provide better results with a small number of data points.

The K-S test, instead of quantizing the data first, is a continuous method, since it looks directly at the observed cumulative distribution function and compares it to the theoretical or expected c.d.f. The cumulative distribution function $F_O(t)$ may be evaluated from data at some point, t^* , by:

$$F_O(t^*) = \frac{\text{Number of components failing by } t^*}{\text{Total number of components on test} + 1}$$

One is added to the denominator to reduce bias. The theoretical cumulative density function $F_E(t)$ may be evaluated by integrating the probability density function $f(t)$. If the observed expected cumulative distribution functions are $F_O(x)$ and $F_E(x)$, then

$$D = \max |F_O(x) - F_E(x)|$$

is the K-S statistic for a one-sample statistic. A two-sample procedure also exists for comparing two samples. The K-S statistic represents the largest deviation of observed values from expected values on the cumulative curve. D is then compared to tables of critical values and, if it exceeds the critical value at some predetermined level of significance, it is concluded that the observations do not fit the theoretical distribution chosen.

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