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Preface

This document was prepared by the Institute for Defense Analyses for the Office of the Deputy Under Secretary for Industrial Affairs. The work was performed under the task order Integrated Diagnostics and Improved Affordability for Weapons and Support Systems. It addresses an objective of this task, to identify effective approaches to the application of commercial off-the-shelf assemblies to weapon systems.

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Contents

Tables

Executive Summary

A shrinking defense market and a growing commercial electronics marketplace are causing the Department of Defense to relax restrictions against using commercial grade electronics in military products. But are these commercial electronics devices adequate to meet the needs of defense products in hostile operating and non-operating environments for long periods of time? To help answer this question, this document looks at the ways in which electronics can fail and at the specific requirements for electronics in military and commercial products.

Reliability Assessment Methods

Many electronics failures result from manufacturing processes. Recent electronic product evaluations at the Air Force Research Laboratory (AFRL) have found that product integrity issues were mostly assembly related. Moreover, reliability testing can induce failures. Traditional reliability assessment methods have focused on these early life cycle problems and haven't adequately addressed other failures that occur later in the product's life cycle, often due to operating or non-operating (storage and dormancy) conditions. To remedy this situation, researchers at AFRL and elsewhere are now investigating new methods of reliability assessment including the Physics of Failure (PoF) approach.

Whereas traditional reliability assessment methods focus on reliability prediction, the PoF approach is concerned with preventing, detecting, and correcting failures associated with the design, manufacture, and operation of a product. The basis for the PoF approach is the definition of the product requirements, including exposure to such stresses as temperature, humidity, vibration, shock, corrosion, radiation, and electricity during operation and non-operation to determine how the product might fail. A reliability assessment is then conducted to target the dominant failure site and to determine whether a product will survive for its intended life or whether other measures must be taken to increase its robustness.

Operating Environment Stresses

In general, fixed ground military equipment resides in controlled environments and isn't subjected to the harsher operating environments of mobile ground, ship, aircraft, missiles, and space equipment. What then are the stresses to which military products are exposed? Examples of environmental stress follow.

Temperature

Low and high temperatures can affect the basic physical properties of semiconductor materials and junctions which, in turn, affect the device- and system-level performance parameters. Temperatures can also cause fatigue, distortion of assemblies, and rupturing of seals due to different coefficients of thermal expansions. The electric propulsion system of a main battle tank can reach temperatures of up to +200°C while aircraft operating temperatures can reach +300°C. To stay within MIL-STD-883[1] upper limit of +125°C, these systems must employ cooling measures—which add weight and costs—and consume power. Recent research has found that these limits may be unduly restrictive and that many systems can perform adequately up to +200°C without changes. However, high temperature electronics above +220°C is an important area of research for the military.

Low temperatures are also of concern. Currently, systems requiring operation at -40°C and lower use military grade, hermetically sealed ceramic packaged microelectronic circuits. The limited availability and high cost of these devices make commercial plastic encapsulated microcircuits (PEMs) an attractive alternative. Recent research has found little evidence of problems with PEMs at temperatures as low as -65°C.

Shock and Vibration

Shock and vibration are considerations for missiles, high-thrust jets, and rocket engines during operation. Much of the shock and vibration research is concerned with developing models to assess these stresses for PoF analysis.

Corrosion

Moisture or contaminants can cause corrosion failures. Moisture is a special consideration for shipboard military products: combined with the corrosive effects of salt, it can have a devastating effect on electronics. Humidity can also promote the growth of fungi and mold which also cause corrosion. Missiles, in particular, experience heavy exposure to bacteria and fungus. Because they aren't hermetic, plastic packages are at risk from humidity, although the last decade has seen many reliability improvements in PEMs in this regard. In a recent study, PEMs were exposed to 100% relative humidity (non-precipitation) and immersed in water to a depth of 1 meter for 20 minutes without leakage.

Contaminants such as sand, snow, and salt can erode surfaces and penetrate into or between components that appear sealed. They are a particular problem in desert or arctic environments. As with moisture, a product's hermeticity will determine the amount of contaminants that enter the product. Conformal coatings are used to protect printed wiring boards from humidity, corrosive gases, solvents, dust, and sand. Worldwide solvent restriction legislation is causing a transition from

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[1] *Test Methods and Procedures for Microelectronics*, 15 November 1991.

solvent-based urethanes, acrylics, and paraxylene to solid silicone coatings. Moreover, the silicone coatings have been shown to outperform solvent-based coatings. In the 1980s, the automotive industry's usage of conformal coatings surpassed that of defense for the first time. While the automotive industry has switched to silicones, defense continues to use the older coatings partly because their lower production volumes and longer product life cycles do not economically justify switching at this time.

Radiation

Radiation-hardness assurance (RHA) is critical for components used in satellites and avionics systems as well as in military systems designed to survive radiation from the explosion of nuclear weapons. Hermetic devices are currently preferred for RHA. However, there is some evidence that PEMs can withstand the effects of radiation. Moreover, commercial applications, such as nuclear-power plants and therapeutic radiation equipment, also require RHA. This should spur the development of commercial-grade RHA devices.

Electricity

Electricity can also cause electronics failures. Electromigration and electrical failure mechanisms from high temperatures are of particular concern to the military.

Non-Operating Environment Stresses

The two main non-operating environments are storage and dormancy. Storage is where the electronics are totally inactivated and residing in a storage area. Dormancy is the state in which the equipment is in its normal operational configuration and connected, but not operating. Temperature, shock and/or vibration, and corrosion account for most non-operation failures. For example, low temperature non-operating requirements can exceed operating requirements. During non-operation, not only are the electronics themselves not generating heat but environmental control systems aren't operational. This is true for missiles which are often stored for long periods in cold climates.

During shipping, handling, and transportation, electronics are subjected to substantial shock and vibration. Because shock and vibration cause cracking, PEMs, which are mechanically more rugged, are preferred to ceramic packaging. What isn't known (yet) is the long-term storage life of PEMs, an important consideration for missiles that have a storage requirement of 20 years. A study of PEMs stored and operated for 10 to 15 years didn't show any appreciable degradation due to storage. However, more research is underway.

Research is also being directed at the long-term moisture reliability of PEMs. The research includes accelerated testing to simulate the effects of long-term storage, degradation analysis, and assessing the remaining life of intermittently used assemblies.

Electrical failure, electrolytic corrosion, and radiation failure are generally not problems in non-operating environments. Likewise, high temperature failures do not occur in non-operating environments where—even in full solar radiation—products do not generally reach temperatures above the MIL-STD-883 limit of +125°C.

Conclusion

As summarized in the next table, there are many cases where commercial grade electronics meet the operating and non-operating environment requirements of military products. When devices cannot meet military requirements, other measures must be taken. This can include ruggedizing the devices or redesigning the boards or systems in which they reside. In some cases, it may be most cost effective to buy spare MilSpec parts and store them. New reliability assessment methods that focus on requirements, root causes of failure, and dominant failure sites rather than reliability prediction will help the military make these decisions.

Table ES-1. Summary of Conclusions

Environmental Stress	Conclusion
High temperatures	Commercial devices are adequate in most military environments. Solders used in second and third level packaging begin to lose structural integrity and melt at 183°C. Where temperatures exceed 200°C, it is necessary to consider substituting silicon-on-insulator or gallium arsenide devices together with ceramic packaging.
Low temperatures	Commercial devices are adequate for temperatures as low as -65°C. Since low temperature requirements in non-operating environments are more stringent than in operating environments, devices requiring storage at low temperatures may have to be MilSpec.
Shock and vibration	Since plastic packaging is better suited to withstand shock and vibration stresses, commercial devices are adequate for most military needs. Only when vibration levels exceed 9g are military devices required.
Corrosion from moisture or contaminants	Commercial devices are adequate up to 85% RH. Only in situations where RH approaches 100% might MilSpec devices be required. While recent studies of PEMs have found them to be reliable after exposure to 100% RH, long-term (>10-15 years) storage moisture reliability is still unknown. Commercial (solid silicone) conformal coatings to protect PWBs from moisture and contaminants outperform military (solvent-based) coatings in harsh environments of humidity and salt atmosphere, suggesting that commercial methods are superior to MilSpec and should be adopted by the military.
Radiation	Hermetic (MilSpec) devices are still needed for most military applications, although commercial applications are driving the development of commercial radiation hard devices.

g - gravity; PWB - printed wiring board; RH - relative humidity; PEM - plastic-encapsulated microcircuit; MilSpec - Military specification.

Chapter 1. Introduction

1.1 Purpose

With the end of the Cold War, Department of Defense (DOD) budgets have been reduced, resulting in lower demand for defense products. This has caused some suppliers of military grade parts, such as electronics, to exit the industry and others to consolidate. At the same time, commercial demand for electronics has intensified. Consequently, the military is a less powerful buyer in the total electronics market than it was previously. For example, in 1993 the DOD Microcircuit Planning Group estimated a decline in the military portion of the microelectronics market from 16% in 1975 to 1.7% in 1995 [DMPG 1993]. The final result of this is that the military can no longer afford to demand military-specific electronic parts and must turn to the commercial electronics marketplace to satisfy defense needs. The purpose of this document is to describe the state of the art and state of practice in using non-military electronics in military products.

1.2 Background

The need to use commercial parts is causing DOD to reform military specifications (MilSpecs). In his June 29, 1994, memorandum entitled *Specifications and Standards: A New Way of Doing Business*, Secretary of Defense William Perry characterized detailed military-unique requirements as barriers to DOD in accessing the commercial industrial base [Perry 1994]. The objective of MilSpec Reform was to:

- Break down those barriers in order to save money,
- Remove impediments to getting state-of-the-art technology into weapons systems, and
- Facilitate the diversification into commercial markets of firms that have traditionally produced goods primarily, if not solely, for defense [Bergmann 1996].

For example, former MilSpec prohibitions of plastic packages are being relaxed in favor of commercially available plastic packages that can attain performance specifications at a reasonable cost and availability. (See Section 3.3 on page 28 for details on one such package, the plastic-encapsulated microcircuit (PEM).)

Reform is also addressing recent questions about the integrity and auditability of traditional electronics reliability prediction methods as prescribed by MilSpecs.[1] These methods are costly to implement, lack insight or control over the actual cause of failure, and are unable to address design and usage parameters that most influence reliability [Pecht 1996, 10]. For example, in March of 1996, the Army directed that MIL-HDBK-217[2] not appear in a Request for Proposal because it had been shown to be unreliable and its use could lead to erroneous and misleading reliability predictions [Decker 1996]. DOD plans to cancel this Handbook as soon as a nongovernment standard replacement becomes available.

Technological changes also have made some MilSpecs obsolete. For example, the widespread use of fine pitch components, different lead configurations, and the recent increase in the use of ball grid array technology have led to different inspection needs for today's assemblies. Whereas the military has traditionally used visual inspection of solder joints, it has recently been incorporating automated inspection. [Reid 1994] The Air Force Research Laboratory[3] (AFRL) recognized this situation in the Spring 1994 issues of *IEEE Reliability Society Newsletter* when it noted that the MIL-STD-883[4] screens are "impractical or need modification for new technologies and add little or no value for mature technologies..." DOD plans to retain MIL-STD-883 only until a suitable nongovernment standard is available for use.

Appendix A shows the status of 25 military reliability and maintainability standards related to electronics. Many are being cancelled or are planned for cancellation as soon as commercial standards become available. Moreover, several have been converted to handbooks or performance specifications.

1.3 Document Organization

Chapter 2 describes the approach used by the IDA study team. Chapter 3 discusses electronics reliability, including different quality systems, how electronics fail, military products in which electronics reside, and the state of the art in electronics reliability and packaging research. Appendix A lists the status of military standards and handbooks affected by current reliability and maintainability standardization reform efforts. Finally, a list of references, a glossary, and a list of acronyms and abbreviations conclude the report.

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[1] "Reliability" is defined as the ability of an item to perform a required function under stated conditions for a stated period of time [IEEE 1993, 1117].

[2] *Reliability Prediction of Electronic Equipment.*

[3] Formerly the Rome Laboratory.

[4] *Test Methods and Procedures for Microelectronics.*

Chapter 2. Approach

This study reviewed the literature and research on using non-military electronics in military products to assess the state of the art and future directions. Some sources of this information are described here.

U.S. Air Force Research Laboratory (AFRL), Electromagnetics and Reliability Directorate. AFRL is the DOD lead agency for reliability and maintainability. Two AFRL divisions that conduct research in areas of reliability, electromagnetic effects, and computational electromagnetics are the Electronics Reliability Division (ERD) and the Electronics Systems Engineering Division (ERS). ERD investigates the fundamental causes of failure mechanisms in electronic devices and systems. ERS is involved in electromagnetic environmental effects, systems reliability and acquisition reform, and susceptibility/vulnerability assessment. More information on the Electromagnetics and Reliability Directorate is available on the World Wide Web at http://daytona.rl.af.mil/welcome.htm.

Reliability Analysis Center (RAC). RAC is an Information Analysis Center sponsored by the Defense Technical Information Center. It is the focal point in DOD for the acquisition, storage, reduction, analysis, and dissemination of test and operational reliability data on electronic and nonelectronic components and electronic systems. It has approximately 25,000 library documents and reliability data on electrical, mechanical, and electro-mechanical components. More information on RAC is available on the World Wide Web at http://www.dtic.mil/iac/iac_dir/RAC.html.

University of Maryland Computer Aided Life Cycle Engineering (CALCE) Electronic Packaging Research Center (EPRC). CALCE/EPRC is a State/Industry/University Cooperative Research Center of the National Science Foundation, and is sponsored by industry and government members. Its mission is to provide a resource base to support the development of competitive electronic products in a timely manner. The goal of CALCE/EPRC is to help its members design and qualify highly reliable products ten times faster by:

- Performance of cross-disciplinary research in electronics packaging to determine, evaluate, and refine science, practices, and principles for the design, manufacture, and assessment of cost effective and reliable electronic products through carefully selected industrial collaboration projects.

- Development of a forum that fosters a high level of cooperation among academia, industry, and government, and the transfer of technology innovations in a clearly measurable manner for both commercial and military applications.
- Education and training of future engineers, researchers, and leaders by instruction of fundamental cross-disciplinary principles, advanced research concepts, and practical industrial methods.

More information on CALCE/EPRC is available on the World Wide Web at http://spezia.eng.umd/general/center/brochure.html.

Electronic Manufacturing Productivity Facility (EMPF). EMPF was established by the U.S. Navy in 1984 to team with industry to develop, test, and analyze state-of-the-art electronics manufacturing processes and electronics production equipment. Its goal is to achieve consistent production of reliable products for the nation's defense by promoting the use of efficient and cost-effective manufacturing processes and equipment. Facilities include an Electronics Manufacturing Learning Center, a Demonstration Factory, and a Technical Library. More information on EMPF is available at http://empf.arl.psu.edu.

International Electronics Reliability Institute (IERI). IERI is a research institute formed in 1990 from the Electronic Device Engineering Group, Department of Electronic and Electrical Engineering, Loughborough University, United Kingdom. It is mainly concerned with reliability studies on a wide variety of electronic components and structures. Other related programs are concerned with inter-connection technology, thick film circuit development, and active device failure modes and mechanisms. Additional information about IERI is available on the World Wide Web at http://info.lboro.ac.uk/departments/el/research/ieri/index.html.

Chapter 3. Electronics Reliability

DOD products have special reliability requirements related to their operating and non-operating (storage and dormancy) environments. Table 1 shows that military microelectronics are generally exposed to greater temperature ranges, vibration, moisture, shock, and radiation than commercial and even industrial or automotive grade microelectronics. However, some sources contend that the military ranges are too restrictive and that military and non-military reliability requirements are not that different.

Another characteristic of military systems that has an effect on electronics acquisition is their long operational lives (20 years or more). This poses reliability and availability concerns. Not only are suppliers of original devices disappearing but the rate of electronic device obsolescence is increasing. Several years ago, semiconductor technology was readily available for 10 to 15 years. Today's military grade product turns over in about 7.5 years and commercial grade devices become obsolete in about 5 years. [DMS 1996] However, Schultz and Gottesfeld [1995] contend that the telecommunications industry also expects a 20-year life from its electronics products.

In this chapter, the following areas are discussed:

- Section 3.1, Quality Systems, describes the five quality systems prescribed by MIL-HDBK-179A.
- Section 3.2, How Do Electronics Devices Fail?, is organized by electronics product failure mechanisms. Subsections describe the failure mechanism, the military products that it affects, the tests that are used to qualify electronics parts, and research underway.
- Section 3.3, Commercial PEMs, describes the state of practice and state of art with respect to plastic encapsulated microcircuits (PEMs).
- Section 3.4, New Reliability Assessment Methods, describes new approaches to reliability assessment.

Table 1. Microelectronic Devices Environmental Ranges

Typical Market	DSB Report	MIL-HDBK-179	Environment					
	Category Name		Temperature Range	Vibration	Moisture	High g	High Shock	Radiation
Consumer Products	Commercial Products (3 to 5 year life cycle)	Category 1 Protected	0°C to +70°C					
	Commercial and Industrial Products (5- to 10-year life cycle)	Category 2 Normal	-40°C to +85°C					
Industrial, Communications, and Automotive		Automotive Grade 3	-40°C to +85°C					
		Automotive Grade 2	-40°C to +105°C					
		Automotive Grade 1	-40°C to +125°C	X	X			
Avionics, Shipboard, Tactical Missiles and Munitions	Military Products (10 to 20 year life cycle)	Category 3 Severe	-55°C to +125°C	X	X	X	X	
			-55°C to +125°C	X	X	X	X	X
Space and Strategic Missiles		Category S Space	-55°C to +125°C	X	X	X	X	X

Sources: [DSB 1993; MIL-HDBK-179A 1995, 11, 20]

g - Refers to gravity and equals a unit of force equal to the force exerted by gravity on a body at rest and used to indicate the force to which a body is subjected to when accelerated [Webster 1980, 464].

3.1 Quality Systems

MIL-HDBK-179A[5] provides guidance in the selection and acquisition of commercial (industrial), commercial (consumer), and traditional military microcircuits for military equipments. It gives greater flexibility and responsibility to the equipment developer in selecting devices based on cost-effective performance, designed-in reliability, and high quality for a given application. It prescribes five quality systems:

- Qualified Manufacturers' Listing (QML) (MIL-PRF-38535D)[6]
- Class M and MIL-STD-883 compliant devices
- Automotive quality system
- Commercial (industrial) quality systems
- Commercial (consumer) quality systems

The first two quality systems that MIL-HDBK-179A [1995, 10] prescribes are military quality systems. The *Qualified Manufacturers' Listing (QML)* is a list of manufacturers' facilities that have been evaluated and determined to be acceptable based on the testing and approval of a sample specimen and conformance to the applicable specification in accordance with MIL-PRF-38535D. The QML system has provisions to qualify a product line as capable of meeting a set of radiation requirements. Since an infrastructure is required to support a military program, QML parts cost more than commercial parts.

The Defense Electronics Supply Center (DESC) manages *Class M* products and approves sources by accepting their certification of conformance to the MIL-STD-883 requirements. By contrast, a *MIL-STD-883 compliant* product is produced to vendor-controlled data books or customer-controlled Source Control Drawings, and the government has no control over who offers MIL-STD-883 compliant parts. DESC conducts initial validation audits, on a random basis and at problem companies, of manufacturers offering Class M or MIL-STD-883 compliant products. These parts generally cost less than QML parts because less government oversight and reporting are involved. However, because they aren't produced in high volumes, these parts tend to cost more than non-military electronics parts.

The *automotive quality system* supports a high-volume customer base, addresses dominant failure mechanisms using qualified testing which includes MIL-STD-883, and includes both hermetic and plastic encapsulated parts [MIL-HDBK-179A 1995, 11]. The automotive industry requires electronics with a 10-year life in humid environments averaging 75% relative humidity (RH) at temperatures between -40°C and +125°C [Schultz and Gottesfeld

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[5] *Microcircuit Acquisition Handbook.*

[6] *Integrated Circuits (Microcircuits) Manufacturing, General Specification for.*

1995]. These requirements are similar to those of the military. Moreover, high-volume production means lower prices [MIL-HDBK-179A 1995, 11].

However, National Semiconductor [Paulsen 1995] believes that defense and aerospace customers wouldn't be better off using automotive components. It contends that the automotive industry uses millions each of a handful of devices whereas government uses handfuls each of thousands of part types. Moreover, many of these automotive devices have unique functions of no value in other applications. Most automotive electronics are in the environmentally stable area behind the dashboard, leaving only sensors and cables exposed to the motor's heat and vibration.

The U.S Army asked the University of Maryland Computer Aided Life Cycle Engineering Electronic Packaging Research Center (CALCE/EPRC) to conduct a survey of automaker responses to National Semiconductor's statements. The survey [Jackson 1996] found that the automotive industry uses millions of each of 4,000 different part types and many of these parts have applicability to a wide range of products. Automakers disagreed that the dashboard is environmentally stable because passenger compartments may reach temperatures in excess of +115°F (+46°C). Moreover, numerous plastic components are used in even harsher environments: for example, under the hood and around the anti-lock brake system where parts are qualified between -40°C and +125°C.

Commercial (industrial) quality systems produce products, hermetic or plastic packaged, to meet a particular industry specification. Specifications are restricted to a minimal supplier base, limiting business to those suppliers with the best quality record. These products are characterized by long-term quality and reliability and long-term availability. [MIL-HDBK-179A 1995, 12] In some cases, these requirements are more severe than those of the National Space and Aeronautics Administration (NASA) or the military. For example, Barrett and Koch [1996, 26] noted that paper machine, steel mill, and other extreme industrial environments must deal with high temperatures, harsh chemicals, steam, electrostatic discharge, and many sources of signal interference. In fact, NASA's Reusable Launch Vehicle, which will be put into operation by the middle of the next decade, will include extensive use of COTS subsystems [Rhea 1996].

MIL-HDBK-179A [1995, 6] states that a wide spectrum of performance, quality, and reliability can be expected from *commercial (consumer) quality systems*, depending on the quality standards applied by the company. Devices are offered almost exclusively in plastic packages for use in low-cost, large volume, benign consumer environments. Temperature ranges are generally 0°C to +70°C. Moreover, devices may have a short product life and may be discontinued without notice as the next generation of hardware is introduced.

3.2 How Do Electronics Devices Fail?

Electronic device failures can occur during manufacturing, testing, operating life, and non-operating life of the product. Manufacturing and testing failures occur early in the product life cycle and have been the focus of traditional reliability assessment methods [Caroli 1994]. However, a firm understanding of the operating and non-operating requirements of military electronics is basic to new approaches to reliability such as the Physics of Failure (PoF) approach. These usage parameters help pinpoint dominant failure mechanisms, enabling the engineer to make informed decisions concerning the adequacy of devices for military applications and to prevent future failures.

3.2.1 Manufacturing

The manufacturing process itself can cause many electronics failures. In the electronics product evaluations it has conducted to date, AFRL's Reliability to Achieve Insertion of Advanced Packaging (RELTECH) program has found that, in general, product integrity issues were mostly assembly related [Fayette 1996]. For example, one manufacturer had a problem with excessive moisture internal to the package after sealing. Another had difficulty sealing a new package design. All manufacturers had voiding/delamination issues associated with die attach, substrate attach, or both. During evaluation of high density interconnect (HDI) technology, bubbles were noted in the interlayers of the substrate as well as different via[7] heights.

Other manufacturing-related failures with particular relevance to military electronics are those related to the cleaning of printed wiring assemblies (PWAs). Cleaning is essential to ensure proper removal of contaminants that may lead to high defect rates when exposed to temperature and humidity over time. However, the cleaning process itself can introduce failures. Ultrasonic cleaning is a successful but controversial method for cleaning PWAs. Studies in the 1950s found that ultrasonic energy can damage fragile wire interconnects between the die and the terminal of microelectronic devices. Based on these studies, DOD hasn't allowed ultrasonics to be used when cleaning military PWAs. Component manufacturing and board assembly technological changes have caused the military to reevaluate this position. In 1991, an Electronic Manufacturing Productivity Facility (EMPF) study [Vuono and Crawford 1991] found that ultrasonics is an effective cleaning technique that, when used correctly, won't damage component wire bonds, and thus recommended that ultrasonic cleaning be allowed on military hardware.

A related issue has to do with using ozone depleting sources (ODS), particularly chlorofluorocarbon (CFC) materials to clean rosin fluxes. Various types of fluxes are used in wave soldering and solder reflow processes to facilitate the soldering operation. The most com-

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[7] Via (hole): An opening in the dielectric layer(s) of a multilayer structure, whose walls are made conductive to enable interconnections between conductive layers [Lau 1995, 609].

mon type of flux used in the electronics manufacturing industry (especially military printed circuit board production) is rosin-based flux. Traditionally, CFC-based materials have been used to clean the residues of the rosin flux from assemblies after soldering. With concordance between industrial countries in recent years (i.e., Montreal Protocol), and new restrictions on the use of CFC-based cleaning agents here in the United States, use of alternative fluxes in the electronics industry is becoming more desirable. EMFP has research projects to look at (1) alternative fluxes and (2) alternatives to CFC-based materials. AFRL is also investigating replacements for ODS to remove solder fluxes from PCBs [Moore 1995].

3.2.2 Testing

Several examples illustrate the problem of testing-induced failures. Appendix J of MIL-PRF-38535D says "burn-in shall be performed on all QML microcircuits, except as modified in accordance with Section 4.2, at or above their maximum rated operating temperature" [MIL-PRF-38535D 1995, 113]. However, *The 1990 Motorola Handbook* says "burn-in prior to usage doesn't remove many failures. On the contrary, it may cause failures due to additional handling" [Navy 1995]. Very high test temperatures used during temperature-humidity-bias (THB) testing can precipitate different failure mechanisms than would be seen during normal device operation [THB 1996]. (For more details on the effects of temperature, see Section 3.2.3.1.)

Similarly, high stress levels of the MIL-STD-883, Method 2002.3, Acceleration/Mechanical Shock test may introduce residual stresses to the die attach and the wirebonds which may cause premature device failure [Mshock 1996]. (For more details on the effects of shock and vibration, see Section 3.2.3.2.)

During autoclave testing, contaminants in the autoclave chamber can induce failures which aren't representative of device reliability [Autoclave 1996]. (For more details on corrosion rate, see Section 3.2.3.3.)

3.2.3 Operating Environment Stresses

Electronics reside in many types of military equipment including ground (fixed and mobile) equipment, shipboard equipment, aircraft equipment, missiles and external stores, and space equipment. The environments in which these equipments operate can cause mechanical, corrosion, radiation, and electrical failures in electronics. Table 2 summarizes the operating environment requirements of each type of military product.

As McCluskey et al. [1997] noted, in some cases, the equipment is subjected to more than one environmental stress at a time. For example, aircraft equipment (jets, turboprops, and helicopters) experience simultaneously thermal stress, vibration, humidity, and input voltage. Moreover, specific conditions depend on the type of aircraft on which the equipment is installed, its location within the aircraft, the aircraft mission profiles, the equipment class designation, maximum aircraft speed, duration of flight at that speed, altitude and ambient air properties, electronics packaging and mounting techniques, internal electrical losses, type of cooling for the compartment in which the equipment is located, and the type of cooling equipment which is being used.

Like avionics, space applications packaging requires attention to mechanical shock and vibration resistance, internal thermal management, and electromagnetic control [Charles and Hoffman 1993]. In addition, as Duston et al. [1995] pointed out, spacecraft electronic systems must survive and operate reliably in intense space environments for long periods of time. Radiation, temperature variations, spacecraft charging, surface contamination, and micrometeoroids/space debris present environmental challenges to long-term survivability.

In contrast, equipments designed for fixed-ground installations are generally located in controlled environments with little exposure to harsh conditions [MIL-HDBK-781A 1996, 68].

Table 2. Military Product Operating Environment Requirements

Operating Env. Reqs.	Fixed Ground	Mobile Ground	Shipboard	Aircraft	Missiles	Space
Temperature		<+200°C		<+300°C	-50 to +75°C	yes
Vibration	nominal	yes	yes	yes	yes	yes
Shock	transit drop	general & transit drop	general & transit drop	general & transit drop	small	yes
Moisture		0 to 100% RH	100% RH	0 to 100% RH	100% RH	
Corrosion		yes	yes	yes	yes	
Bacteria/ Fungi		yes	yes	yes	heavy	
Salt		yes	severe	yes	yes	
Radiation				yes	yes	yes

3.2.3.1 Temperature

Temperature can affect electronics in at least two ways:

- First, it can affect the basic physical properties of semiconductor materials and junctions, which, in turn, affect the device- and system-level performance parameters. For example, the speeds of microelectronic devices are sensitive to high and low temperatures. If temperature extremes cause the timing of the microcircuit to increase or decrease beyond system operating thresholds, the software and/or hardware may experience a failure.
- Second, changes in temperature or the rate of temperature change can produce mechanical stresses causing dimensional changes, fatigue, and fracture failures. For

example, the die, substrate, leadframe, and case of a microelectronic package have different coefficients of thermal expansion, which can cause fatigue and fracture of package components. Or ultraviolet (UV) rays and intense heat can deteriorate materials and promote aging.

The climate as well as the military equipment itself can be responsible for high temperatures. Pecht and Pecht [1995, 10] describe the range of recorded earth climate temperature extremes as -80°C to +58°C. Desert temperatures (+35°C to +50°C) and tropical temperatures (+31°C to +41°C) are high with daily temperature changes of up to 20°C. Moreover, in full solar radiation, products can reach temperatures exceeding +70°C. MIL-HDBK-781A [1996, 69] notes that climate is a particular consideration for mobile ground equipment which includes wheeled vehicles, tracked vehicles, shelter configurations, and manpacks.

In addition, aircraft, missiles, and tanks generate heat that can be damaging to their electronics. Sensors in a combustion chamber of a jet engine may experience temperatures of +300°C or higher. F-15 skin temperatures range from +90°C to +200°C [McCluskey et al. 1997, 238]. Even in commercial avionics, high speed civil transport temperatures reach +193°C [McCluskey et al. 1997, 226]. And the Air Force's future More Electric Aircraft is expected to reach temperatures of +350°C [McCluskey et al. 1997, 235].

As a missile leaves the ground and passes through the earth's atmosphere, the surface of the missile is aerodynamically heated [Zedro and Lamphear 1962]. Even the power semiconductors in the electric propulsion system of a main battle tank may operate at temperatures close to +200°C [McCluskey et al. 1997].

Cooling

Cooling is currently required to maintain electronics at the upper MIL-STD-883 limit of +125°C. For example, closed-loop environmental control systems (ECSs) cool most avionics and power control electronics on fighter aircraft. Today's ECSs are large in size and weight, add extra costs, and consume great amounts of power. [McCluskey et al. 1997]

Various electronic countermeasures stores also use forced air from the aircraft's jet stream for cooling. For example, the Low Altitude Navigation and Targeting Infrared and Targeting System for Night pods on the F-15 and F-16 aircraft use ram air and a small self-contained poly-alfa olefin/freon ECS to condition electronics. Disadvantages include reduced aircraft performance, aerodynamic drag, added ECS weight, and single-point failure [McCluskey et al. 1997, 237]. Even dumping the electronics heat to the outer skin via thermal conduction has the disadvantage of restricting electronics mounting to the outer case of the weapon.

Low Temperatures

Pecht and Pecht [1995, 9] explain why low temperatures also pose problems. Arctic temperatures can be -29°C with large daily temperature changes of 20°C in spring and fall. This contributes to decreases in yield strength, ultimate strength, and ductility. Polymeric materials, including plastics, become brittle. Temperature coefficients of components—such as capacitors, resistors, and inductance devices—can also change their performance. Plastic seals begin to leak due to shrinkage and cracking. "Tin pest"[8] occurs at temperatures of 0°C and can cause electrical breakdown in circuits by bridging conductors.

In 1992, Jones and Marsh [1992] conducted a study to determine the appropriate low-temperature operating requirement for the improved Tomahawk Ship Launched Cruise Missile. The costs to develop and qualify a new rocket motor for operation at the typical shipboard military low-temperature extreme of -13°F (-25°C) seemed excessive. The authors concluded it wouldn't be necessary to design the missile components to operate at temperatures below 25°F (-3.8°C) because the Armored Box Launcher and the ECS would be able to maintain temperatures inside the launcher above 25°F (-3.8°C). However, the study didn't address storage and transportation environments which are more stringent. (See Section 3.2.4.1 for details on temperature requirements in non-operating environments.)

Currently, systems requiring operation at -40°C and lower usually use military grade, hermetically sealed ceramic packaged microelectronic circuits. The limited availability of these devices has prompted military and aerospace product developers to consider commercial or industrial grade PEMs. (See Section 3.3 for more details on PEMs.) However, their reliability at low temperatures hasn't been well characterized. Delamination and cracking of PEMs at low temperatures could lead to wire breakage as well as corrosion during subsequent high temperature exposure. CALCE/EPRC Project C96-25 [1996] characterized the effects that limit the use of PEMs at low temperatures to -65°C and identified potential failure mechanisms. It found little evidence of delamination and cracking at temperatures as low as -65°C even at the fastest ramp rates and with devices saturated with moisture [C97-05 1996].

Temperature Screens

MIL-STD-883, Method 1010.7, Temperature Cycling is the screen used to test the durability of a package undergoing extreme temperature variations over a given period of time. Table 3 compares Test Condition C from MIL-STD-883, Method 1010.7 with some test specifications used by industry. Most of the industry specifications are equivalent to the MIL-STD.

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[8] Tin pest: A whiskery type of single-crystal growth on tin-plated finishes. Although humidity encourages whisker growth, whisker growth should not be confused with corrosion [Pecht and Pecht 1995, 13].

Table 3. Temperature Cycling Test

Test Specification	Low Temperature (C)	High Temperature (C)	No. of Cycles
MIL-STD-883, Method 1010.7, Test Condition C	-65°	+150°	10
Motorola	-65°	+125°	1,000
Intel	-55°	+125°	500
Signetics	-65°	+150°	500
Micron	-65°	+150°	1,000
Texas Instruments	-65°	+150°	500
American Micro Devices	-65°	+150°	1,000
National Semiconductor	-65°	+150°	1,000

Source: [TEMPCYCL 1996]

Table 4. Thermal Shock Test

Test Condition	High Temp. (C)	Low Temp. (C)	Recomm. Fluid
A	+100°	0°	Water
B	+125°	-55°	Perflourocarbon
C	+150°	-65°	Perflourocarbon

MIL-STD-883, Method 1011.9, Thermal Shock is used to test the reliability of a package when it undergoes a rapid change in a field or handling environment. The procedure is to cyclically immerse the package in fluids that are maintained at specific temperatures. Testing is conducted for a given number of cycles, usually ending in the highest stress cold bath. After thermal shocking, the devices are allowed to return to room temperature, then electrical tests and visual inspections are performed. For hermetic packages (ceramic and metal cases), the device is subjected to hermetists tests. Table 4 shows the MIL-STD test conditions for thermal shock. J-leads are especially susceptible to thermal shock. According to McCluskey et al. [1997], the best methods to avert thermal shock are to enhance adhesive flux by decreasing the glass transition temperature or to stiffen the board with conformal coatings.

CALCE/EPRC believes that the military temperature limits of -55°C to +125°C may be unduly restrictive, contending that many systems should be able to perform adequately up to +200°C with no changes. In other cases, system failures can be avoided by selecting different materials or varying design parameters to accommodate higher steady-state temperature use.

High Temperature Packaging Considerations

McCluskey et al. [1997, 162] describe first-level electronics packaging considerations for high temperatures as follows. For temperatures up to +135°C, standard high-density devices and package technologies can be used. For temperatures up to +200°C, standard high-density devices and packaging technologies can be used with some alterations. Above +200°C, it is necessary to consider substituting silicon-on-insulator or gallium arsenide devices together with ceramic packaging.

However, according to McCluskey et al. [1997, 163], second- and third-level packaging considerations are more stringent. Environments exceeding +183°C cause solder to melt; application temperatures that don't exceed the melting point but approach it can cause the solder to lose structural integrity.

Material advances are resolving significant barriers associated with mechanical and electrical properties such as strength, conductivity, and fatigue life. For instance:

- EMPF has been working with electronic, lead-free solder, and polymer manufacturers to implement these new interconnect materials into functional commercial and military electronics [Condbaa 1997; Guy 1995].
- The Navy/Best Manufacturing Practices High Temperature Solders project at CALCE/EPRC seeks to learn more about the reliability issues in developing lead-free solders for high-temperature applications by qualifying the durability metrics of promising solders and relating these metrics to microstructure and process parameters [Solder 1997].
- Another CALCE/EPRC project, Assessment of High-Temperature, Fatigue-Resistant Solders, will assess the manufacturability and durability of candidate melting point solders for down hole drilling operations [C97-24 1997].

Hybrid circuit technology, often with ceramic substrates, has long been known for high temperature capability [McCluskey et al. 1997]. And Chen et al. [1990] successfully used hybrid multichip packaging technology for operation at low temperatures (-140°C) in the construction of an advanced astrometric sensor array.

Temperature Research

Recognizing that temperature effects on electrical performance propagate from device material properties to system parameters, CALCE/EPRC is conducting research on requirements for thermal management and analysis. Project C96-17 [1996] has found that at the device level, silicon devices can operate over a large range of junction temperatures.

However, at the circuit level, the acceptable range of performance parameters depends on the type and level of criticality of the application. Parameter shifts in electronic devices occur for both high and low temperatures. Along with progressive changes, performance/temperature relationships often display threshold characteristics. Most of the parameter shifts in microelectronic devices are temporary and reversible. With reductions (or increases) in temperature, electrical parameters return to normal levels. CALCE/EPRC recommends involving thermal analysts early in the design process to:

- Identify system-level performance parameters that are critical for proper functioning,

- Identify device-level performance parameters that control the critical system-level parameters,
- Determine the acceptable range for the critical device-level performance parameters, and
- Identify temperature thresholds for performance parameters.

High temperature electronics above +220°C are still in the research stage. McCluskey et al. [1997, 4-5] contended that a military market in high temperature electronics is developing, leading to a civilian market. Commercial high temperature electronics applications include commercial aircraft, automotive, geothermal well logging, and chemical processing.

In addition to the solder projects mentioned above, CALCE/EPRC has several projects related to high temperature electronics, including:

- Use of Electronic Hardware at Elevated Temperatures (Project C95-18).
- Testing of Electronic Hardware at Elevated Temperatures (Project C96-21).
- Physics of Failure of High Temperature Capacitators (Project C96-22).
- Uprating of Commercial Parts for Use in Harsh Environments (Project C97-05). (See Section 3.4 for details on new reliability assessments methods.)
- High Temperature Distributed Control Systems (Consortium Project).

Computing Devices International in Minneapolis is leading an industry research effort [COTS 1995] to determine whether direct chip attach (DCA) technology can withstand the temperature extremes of military avionics applications. If the results are favorable, DCA technology may be used in military programs such as the U.S. Navy's AYK-14 standard airborne computer. Computing Devices International will characterize low-cycle fatigue performance of solder ball flip-chips with underfill on MCM-L[9] substrates, as well a bardic gold-wire bonding. This particular effort is being done in cooperation with Microelectronics Computer Technology Corporation, Naval Surface Warfare Center Crane Division, Aluminum Design Corporation, and Research Opportunities, Inc.

3.2.3.2 Shock and Vibration

Shock is defined as a sudden change that affects the location, velocity, acceleration, or forces in a structure. It may occur during the assembly, transport, or handling of the electronic packaging. It is therefore a consideration for all types of military equipment. Failures of electronic systems under shock are primarily due to high stress which can cause permanent deformation, crack extension or failure, and large deflections. These, in turn, can cause collision between objects such as adjacent wirebonds, components, and circuit boards [C96-03 1996]. Similarly, vibration can cause cracks

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[9] MCM-Ls are multichip modules using advanced forms of printed wiring board technologies to form the copper conductors on plastic laminated-based dielectrics [Lau 1995, 588].

and crack propagation in package components. Dynamic external loads to which electronics packages are exposed during shipping, handling, and/or operations give rise to stresses in the leads causing fatigue failures. For peripheral leaded packages, the corner leads are the most highly stressed leads.

Table 5 shows transportation acceleration extremes. The U.S. Army has measured shock stresses at 10 g on trucks and 300 Hz on railroad cars [Army 1978]. A study of published and unpublished reports on environmental stresses associated with torpedoes by the Weapons Quality Engineering Center [WQEC 1980] placed particular emphasis on vibration and shock data.

Table 5. Acceleration Extremes in Transportation

Mode	Acceleration (g)	Frequency (Hz)
Truck	7	300
Aircraft	7	1100
Railroad Car	1	300
Ship	1	70

Source: [Pecht and Pecht 1995, 6]

Hybrid circuit technology, often with ceramic substrates, has long been known for its immunity to shock and vibration [McCluskey et al. 1997]. However, in a study [Dylis and Ebel 1993] performed for the U.S. Air Force on a missile remote interface unit in a fighter aircraft, vibration levels were found to exceed power spectral density design limits by almost two orders of magnitude in the range of 40 Hz and 60 Hz, causing the premature failure of an expensive hybrid. The major cause of failure for these hybrids was broken leads.

Shock/Vibration Screens

MIL-STD-883, Method 2002.3, Acceleration/Mechanical Shock is used to screen parts used in avionics and space environments. This test subjects the part to accelerations, after which the package is inspected. This method mandates that a 1,500 peak g level be applied for a duration of 0.5 milliseconds (Test Condition B). The acceleration is applied in the Y1 direction (the one in which the element tends to be removed from its mount).

MIL-STD-883, Method 2001.2, Constant Acceleration is used to determine the effects of constant acceleration on microelectronic devices. It is designed to indicate types of structural and mechanical weaknesses not necessarily detected in shock and vibration tests. A constant acceleration of 30,000 g (Test Condition E) is applied to the device for one minute in each of the orientations X1, X2, Y2, Y1, Z1, and Z2.

Several MIL-STD-883 screens pertain to vibration. MIL-STD-883, Method 2026 tests for random vibration, a characteristic of missiles, high-thrust jets, and rocket engines. MIL-STD-883, Method 2005.2 is the test for vibration fatigue (see Table 6).

Table 6. Vibration Fatigue Test

Test Condition	Peak Acceleration (g)	Min. Test Time (hours)
A	20	96
B	50	96
C	70	96

Source: [MIL-STD-883D 1991]

MIL-STD-883C, Method 2020.7, Particle Impact Noise Detection Test is used to detect the presence of loose particles that can cause electrical shorts on the die or between interconnects within a hermetic package. It employs a transducer to measure the sound coming from the package which is shaken. The method specifies two test conditions, as shown in Table 7.

Table 7. Particle Impact Noise Detection Test

Test Condition	Peak Acceleration (g)	Frequency (Hz)
A	20	40 to 250
B	10	60

Source: [MIL-STD-883D 1991]

As Table 8 shows, the MilSpec vibration levels in Table 6 and Table 7 exceed those of Consumer, Industrial, and Automotive products. Fortunately, plastic packaging has the advantage of being both light and mechanically rugged, making it well suited for vibration and shock stresses.

Table 8. Operating Vibration Levels

Product	Vibration (g)
Consumer	0 to 2
Industrial	1 to 3
Automotive	2 to 4
Commercial Avionics	4 to 8
Military	4 to 12

Source: [Boeing 1994, 91]

Shock and Vibration Research

CALCE/EPRC researchers have written a software engine [C96-03 1996] based on the shock spectrum technique for the case of a circuit card assembly (CCA) subjected to a base acceleration. The program reads the shock pulse information such as the pulse shape, the acceleration amplitude, and the period. Then it calculates participation factors for the first few (usually six) natural vibration modes of the structure obtained from the CALCE finite element free vibration solver. The output of the new engine is the shock response of the board in terms of node acceleration, node displacement, and element curvatures. These outputs are needed as inputs for failure models used to assess the life of the CCA. The shock spectrum analysis engine is ready to connect to the interface. It has been calibrated by comparing with theoretical solutions and numerical calculations from a commercial Finite Element Analysis (FEA) code ABAQUS.

Sidharth and Barker [1996] have developed a model for computing the out-of-plane displacement of the corner lead in component-lead-board assemblies subject to bending. The model uses a functional form from an analytic model to capture the basic physics of the problem. The analytic model was then correlated to the results expected from FEA, using design of experiments and analysis of variance. Validation against six independent sets of data found the model to be accurate.

3.2.3.3 Corrosion

Corrosion failures can result from exposure to moisture and contaminants such as dust, sand, salt, or snow. According to MIL-HDBK-781A [1996, 71], humidity and corrosion from salt are of special concern for shipboard equipment. This equipment includes Naval surface craft, Naval submarine, marine craft (Army, landing), and underwater vehicles.

Moisture

Pecht and Pecht [1995, 9-10] describe the climatic conditions that expose electronics to moisture-related and corrosion failures. In the Arctic, moisture can cause cracking as it freezes and expands. The presence of thick moss, muskeg, can turn water acidic in the Arctic, a source of corrosion. The high concentration of dissolved salts in Arctic waters can also cause corrosion. Even condensation from ice fogs can result in lead corrosion.

In the tropics, high humidity, heavy rainfall, and microorganisms cause metals to corrode more rapidly, and electrolytic action between dissimilar metals is accelerated. Moisture absorption lowers surface and volume resistivity of insulating materials, which causes swelling of materials, leading to electrical and mechanical breakdown. Fungi and mold can cause etching on material surfaces. Recognizing the serious threat that fungi posed to the storage and use of ordnance material in diverse world climates, the Army's Ordnance Tank-Automotive Command was engaged in research programs [Lee 1962] to define and control the behavior of ordnance materiel to destruction by fungi very early on (1950-1962).

Low moisture can cause problems as well. In desert environments where the RH is low (only 30%), the low moisture content of the atmosphere can cause some plastics to warp, some materials to lose tensile strength, and materials incorporating organics—such as paper—can disintegrate [Pecht and Pecht 1995, 8-9].

Moisture Screens

The Temperature Humidity Bias (THB) [THB 1996] test is used to test for moisture-induced failures. An applicable standard is EDEC-STD-22 TM-A 108. The test requires the devices to undergo a constant temperature, elevated relative humidity, and electrical bias (constant or intermittent, based on device type). Voltage cycling may be required to prevent the device from heating up and preventing moisture effects from occurring. Standard THB conditions are 85°C/85% RH at operating voltage levels, applied for a minimum of 1,000 hours. Electrical tests are performed after the THB stressing to detect parametric drifts associated with corrosion of susceptible parts.

Autoclave [1996] testing (JESD-22 Method A102-A), used to measure plastic package moisture resistance, can be performed with or without bias. In the unbiased test, the devices are sealed in an autoclave chamber containing deionized water. Bias is used to accelerate electrolytic and galvanic corrosion. The storage time and temperature of the test vary with the application. Measurements are performed at the end to evaluate moisture resistance. Industry examples can be found in Table 9. Since no acceleration factors exist, relating the results of this test to true field performance is inaccurate at best.

Table 9. Industry Specifications for Autoclave Testing

Company	Temperature (C)	Pressure (psi)	Duration (hours)
Motorola	121°	15	96
Intel	121°	N/A	96
Texas Instruments	121°	15	240
Signetics	127°	20	336
Micron	121°	15	96
American Micro Devices	121°	15	168
National Semiconductor	121°	15	500

Source: [Autoclave 1996]

Contaminants

Contaminants such as sand, dust, snow, and salt can erode surfaces and penetrate into or between components that appear sealed in desert environments. As Pecht and Pecht [1995, 9] noted, snow takes on the character of sand at low Arctic temperatures (-29°C). Glacial dust, similar to desert dust, also causes corrosion and erosion.

MIL-STD-883, Method 1009.8, Salt Atmosphere (Corrosion) is used to evaluate the corrosion resistance of leads and leadframes. Specimens are exposed to a salt fog with a pH of between 6 and 7.5 for 96 hours at 35°C.

Conformal Coatings

Conformal coatings are used to protect printed wiring boards (PWBs) against humidity, corrosive gases, solvents, dust, and sand. They are also used to stiffen boards to avert thermal shock. Military specifications governing the assembly of PWBs for DOD specify that a conformal coating be used as an insulating compound for environmental protection of the assembly [BCC 1994, 44]. Consequently, 95% of all defense PWBs are coated [BCC 1994, xv].

As Table 10 shows, the Avionics/Defense Sector uses solvent-based urethanes, acrylics, and paraxylene, while commercial industries, led by the automotive industry, are moving to solid silicone methods or other solid materials that are UV cured. Worldwide solvent restriction legislation is causing the transition from solvent-based coatings to solid formulations, with new cure systems for rapid processing. Although the solid coatings cost more, these costs are offset by productivity savings because the solids are easier to apply and cure more rapidly.

Table 10. 1993 U.S. Conformal Coating Sales by Type and Industry

Chem. Type	Automotive		Avionics/Defense		Industrial		High Tech Niche		Total	
	$M	%	$M	%	$M	%	$M	%	$M	%
Silicones	16.7	79.5	1.0	7.1	2.2	31.4	3.4	56.8	23.2	48.6
UV Cure Types	3.1	14.7	0.5	3.6	0.2	2.9	0.2	3.3	4.0	8.3
Urethanes	0.1	0.5	5.6	40.0	1.5	21.4	0.5	8.3	7.7	16.0
Acrylics	1.0	4.8	3.3	23.6	2.3	32.8	1.2	20.0	7.8	16.3
Paraxylene	0.0	0.0	3.3	23.6	0.2	2.9	0.2	3.3	3.7	7.7
Epoxy	0.1	0.5	0.3	2.1	0.6	8.6	0.5	8.3	1.5	3.1
Total	$21.0	100%	$14.0	100%	$7.0	100%	$6.0	100%	$48.0	100%

Source: Adapted from [BCC 1994, 17].

The low-production volumes of the Avionics/Defense Sector cause manufacturers to select equipment and coatings that require less expensive fixed costs for equipment and are more labor intensive. These are typically older solvent-based coatings. Moreover, the longer cure times of solvent-based coatings aren't perceived as a problem in low-production environments. Finally, the reliability of newer UV-cured coatings is questionable in areas not directly exposed to UV radiation, such as the areas under components.

However, a 1985 Raytheon study [Venuti and Chin 1985] testing conformal coatings for performance on copper thick film circuitry in harsh environments found that in all phases of the test plan, the silicone coating outperformed the urethane and exhibited no failures after 30 days of humidity with bias testing. In addition to subjecting the coatings to salt atmosphere, temperature cycling, and humidity with bias, the coatings were tested as to repairability (i.e., ease of removal and performance after recoating).

Conformal Coating Research

EMPF has recognized that integrating advanced coating systems into highly reliable military electronics applications requires more measurement control. In a collaborative effort [Surfspec 1997], EMPF is developing a low-cost, real-time surface spectroscopy system to measure oxide and coating character of metallizations on components and boards in conjunction with organic and metallic protective coatings and platings. The effort is expected to produce a prototype system for beta site implementation.

3.2.3.4 Radiation

Radiation-hardness assurance (RHA) testing is critical especially for components used in satellite and avionics systems and for military systems designed to survive radiation from the explosion of nuclear weapons. For these devices, radiation effects must be superimposed upon other natural environment conditions. Appendix A of MIL-HDBK-179A [1995] describes four radiation responses of semiconductor devices, their causes and effects, and the mitigation methods to be considered for each response. The four radiation effects are (1) Single-Event-Effects, (2) Total Ionizing Dose, (3) Neutron and Proton (bulk displacement) Damage, and Dose-Rate and Internal Electromagnetic Effects.

- Single-Event-Effects (SEE) are caused by the impact of galactic cosmic rays, solar enhanced particles and/or energetic neutrons and protons, and alpha particles. Effects include single-event-upset, single-event-latchup, single-event-burnout, single-event-gate-rupture, and single-event-hard-error. Mitigation methods include RHA parts, shielding for protons and neutrons only, and system design. SEE can be especially important for high-flying aircraft where neutron fluxes may be significant, and in aircraft employing current generation micron and sub-micron microelectronics technologies where very little of the neutron's energy needs to be imparted to the devices to produce SEE [Dussault 1995].
- Total Ionizing Dose is caused by radiation belts, solar radiation, nuclear reactors, and nuclear weapons. Effects include frictional failure, increased leakage and standby currents, timing degradation, and decreased I/O drive capability. Mitigation methods include RHA parts, shielding, and circuit design.
- Neutron and Proton (bulk displacement) damage is caused by radiation belts, solar radiation, nuclear reactors, and nuclear weapons. Effects include gain degradation, increased noise, increased dark current for charge coupled devices, and secondary circuit effects from these. Mitigation methods include RHA parts, shielding for protons, and circuit design.
- Dose-Rate and Internal Electromagnetic Effects are caused by nuclear weapons threats. Effects include current and voltage transients, upset, latchup, snapback, and high dose rate burnout. Mitigation methods include RHA parts, shielding, and subsystem design.

Table 11 describes the threat environments and device requirements for various military and non-military applications exposed to radiation. It shows that many commercial and military requirements are similar.

Currently, insufficient data exist regarding the use of PEMs in applications requiring RHA, and research is needed. However, preliminary data generated by Harris Semiconductor [Schultz and Gottesfeld 1994, 6] on silox passivated complementary metal-oxide semiconductor integrated circuits in 16-lead plastic dual-in-line packages demonstrated no device degradation after an exposure level of 300 Krads.

Table 11. Application/Threat vs. Device Requirements

Application	Threat	Representative Device Requirements
ICBM and Strategic Interceptor Missiles	Primary: - Neutron irradiation - Dose-rate upset/survivability Secondary: - Total ionizing dose	Neutron irradiation $>10^{13}$ n/cm^2 Dose-rates $>10^8$ rad/s Total dose < 10 Krad(Si)
Military Surveillance, Navigation and Communications Satellites	Primary: - Total dose - SEE - Dose-rate upset Secondary: - Neutron and proton	Total dose $\geq$ 300 Krad(Si) SEE $< 10^{-10}$ errors/bit-day Dose-rate $< 10^8$ rad/s Neutrons$< 10^{12}$n/cm^2
Commercial Communications Monitoring Satellites	Primary: - SEE - Total dose (Nuclear Weapons) Environment (NWE) Secondary: - Total dose (natural) - Neutron and proton	SEE $< 10^{-9}$errors/bit-day Total dose ~ 30 Krad(Si) NWE ~10 Krad (Si)
Tactical Military Systems, including Avionics	Primary: - Neutron irradiation - Dose-rate upset (upset and latchup) Secondary: - Total ionizing dose - SEE (for avionics)	Dose-rate 10^9 rad/sec Neutron irradiation 10^{12}n/cm^2 Total dose < 5Krad(Si) SEE $< 10^{-9}$errors/bit-day
Nuclear Reactor Control and Scientific Systems	Primary: - Neutron irradiation - Total dose	Neutron irradiation $> 10^{13}$ n/cm^2 Total dose > 100 Krad(Si)

Source: [MIL-HDBK-179A 1995, 50]

And despite harsh requirements, the Clementine spacecraft[10] demonstrated that commercial-grade devices—even plastic-encapsulated parts—can do the job in the harsh environment of space [Dustron et al. 1995]. *Not one significant hardware failure occurred during the mission despite the fact that 50% of Clementine's diodes, 80% of the transistors, and 60% of the integrated circuits were commercial parts.* Most of the commercial plastic parts were screened to MIL-STD-883 and selected so as to prevent destructive latchup and to operate in the mission space environment for a full year.

To obtain data on specific microelectronic and sensor systems in the space environment, several engineering experiments were specially developed for the Clementine spacecraft to measure the effects of radiation and the thermal environments on microelectronics. Commercial applications such as nuclear-power plants and therapeutic radiation equipment require RHA parts, which should drive the development of commercial RHA devices.

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[10] Also called the Deep Space Program Science Experiment, the spacecraft was launched to the moon in January 1994.

Radiation Research

In 1995, the Air Force Research Laboratory and the Naval Research Laboratory initiated a joint two-year research program [Dussault 1995] to improve current understanding of single-event anomalies in avionics systems. The team will assess the extent, frequency, and importance of SEE in current and next-generation avionics systems. It will identify the impacts of SEE on avionics system reliability and maintainability and recommend methods for mitigating SEE.

AFRL has another project [Seifert 1995] to assess the electromagnetic (EM) performance of Advanced Packaged Technologies targeted for DOD systems and to establish EM design and packaging techniques to improve EM performance.

3.2.3.5 Electricity

Electrical failure mechanisms generally occur during operation or testing when an external voltage or current is applied. Pecht and Pecht [1995, 12] identify the following failure mechanisms:

- Electrical overstress: The result of higher-than-rated voltage or current induction of a hot-spot temperature.
- Time-dependent, dielectric breakdown: The formation of low-resistance dielectric paths through localized defects in dielectrics.
- Secondary breakdown: From an increase in current density and temperature or a drop in voltage in power transistors.
- Electromigration: From high current density in metallization tracks, producing a continuous impact on metal grains in the tracks, causing the metal to pile up in the direction of current flow and producing upstream voids.
- Hot electrons: When charge carriers that acquire energy from strong electric fields cross the potential barrier at the silicon-silicon oxide interface and cause threshold voltage shifts.
- Hillock formation: Resulting in electromigration.
- Metallization migration: When there is a certain level of current density at a dendrite tip, sufficient liquid medium, and an applied voltage that exceeds the sum of anodic and cathodic potentials in equilibrium with the electrolyte.

Three failure mechanisms only occur from extremely high temperatures (175°C to 400°C):

- Contact spiking: Penetration of metal into the semiconductor in contact regions.

- Surface charge spreading: The lateral spreading of ionic charge from biased metal conductors along the oxide layer or through surface moisture.
- Slow trapping: The trapping of electrons when they cross the potential barrier of the silicon-silicon oxide interface, causing a shift in the threshold voltage.

MIL-STD-883 contains several electrical testing procedures. Methods 3001.1 to 3022 cover digital tests, and methods 4001 to 4007 cover linear tests.

Electrical Failure Research

An AFRL research project [Walsh 1995] is investigating the relationship of basic material properties and electromigration. Interconnects were first recognized as a major reliability problem in the early 1960s with the identification of electromigration as a failure mechanism for operational devices. Electromigration is the movement of conductor atoms with an applied current causing failures by either void or whisker formation. Voids cause open failures when the voids coalesce to cut or slice the interconnect. Whiskers cause failures by shorting when two or more isolated interconnects are joined by a whisker. This basic research project is supported by the Air Force Office of Scientific Research.

The project has developed molecular dynamic analytical models, allowing three-dimensional atomic-level modeling, simulation, and visualization of polycrystalline samples subjected to various stresses. Preliminary results demonstrating thermal expansion, specific heat, self-diffusion, and annealing behavior have been published, and dynamic displays of atomic motion have been developed. Thin-film behavior established with molecular dynamics modeling can be used to aid in the design, manufacture, and application of reliable integrated circuits, and can also serve as input to corollary investigations of electronic materials using finite element analysis. Work will continue to account for the influence of current density and temperature gradients on the reliability of thin metal films used in microelectronic devices.

3.2.4 Non-operating Environment Stresses

Pecht and Pecht [1995, 1] defined the two main non-operating environments: storage and dormancy. Storage is the state in which the system, subsystem, or component is totally inactivated and resides in a storage area. Dormancy is the state in which the equipment is in its normal operational configuration and connected, but not operating.

The usual methods of testing for non-operating environments are *overstresses* and *accelerated wear-out stresses* to simulate the long periods of non-operation [Pecht and Pecht 1995, 89]. Temperature, shock and/or vibration, and corrosion account for most non-operation failures. Several stress conditions and failure mechanisms are unaffected by long-term storage and dormancy, including:

- Electrical failure mechanisms
- High temperature failure mechanisms
- Electrolytic corrosion
- Some radiation failure mechanisms [Pecht and Pecht 1995, 12-14]

Any military equipment that is transported or stored is at risk for non-operation failures. However, missiles are at the greatest risk because they are manufactured in large quantities, stored for lengthy periods (20 years), and are non-recallable for a faulty condition upon launch. Latent reliability problems may render a large portion of a stockpile unfit for service because of inoperable or unsafe electronics. [RAC n.d.] For example, in 1961, corrosion problems were encountered in silo storage of missiles [Gatzek 1961]. Table 12 shows the reliability parameters of missiles.

Malik [1976] and Malik et al. [1976] have analyzed long-term non-operating missile data and have developed reliability models for missiles. In another study, McGarry and Sisul [1977] subjected samples of 200 each of 21 different parts planned for use in the Patriot Missile Systems to a comprehensive test program to determine their storage reliability potential. The Naval Weapons Center at China Lake performs environmental and safety/insensitive munitions testing of live ordnance and ordnance-related items ranging in size from fuzes to large missile systems [Featherston 1990]. Tests include shock, vibration, climatics, fast cookoff, slow cookoff, bullet impact, and free-fall drop.

Table 12. Estimated Extreme Environmental Parameters for Army Tactical Missiles

Parameters	Estimated Values
Maximum temperature	+75°C
Minimum temperature	-50°C
Temperature cycling	$\Delta T \approx 70°C$
Moisture	up to 100% humidity
Thermal shock	small
Mechanical shock & vibration due to transportation & handling	$\approx$ 10 g
Bacteria & fungus	heavy exposure
Nuclear radiation	not applicable
Electromagnetic fields	not applicable

Source: [Livesay 1978]

3.2.4.1 Temperature

In 1978 the Army [1978] characterized temperature extremes in three storage environments:

- Open storage (-42°C to +74°C)
- Non-earth-covered bunkers (-35°C to +47°C)
- Earth-covered bunkers (-5°C to +39°C)

Other extreme temperatures associated with transportation and storage range from -62°C to +71.1°C [1967]. These are all within the 125°C upper temperature screen of MIL-STD-883.

MIL-STD-883, Method 1008.2, High Temperature Storage[11] is used to precipitate defects in packages when they are kept at an elevated temperature. This screen is used only for storage qualification. In the case of ceramic and metal packages, it is followed by a hermeticity test to check for leakage. Table 13 compares MIL-STD-883, Method 1008.2, Test Condition C (the usual test condition) with industry test conditions. As depicted, industry test conditions meet or exceed the MIL-STD tests, suggesting that the MIL-STD-883 limit of 125°C is perhaps too restrictive.

A study of the low-temperature environmental requirements of the improved Tomahawk Ship-Launched Missile shows that non-operation requirements can be more stringent than those of the operating environment [Jones and Marsh 1992]. While the authors concluded that the missile components wouldn't be required to *operate* below 25°F (-3.8°C), the missile and its components must still be capable of being *stored and transported* at temperatures as low as -30°F (-34.4°C)—conditions not addressed by the study.

Table 13. High Temperature Storage Requirements

MIL-STD-883 Test Conditions	Temp. (C)	Min. time (hours)	Industry Test Conditions	Temp. (C)	Time (hours)
C	100°	1,000	American Micro Devices	125°	2,000
C	125°	169	Micron	150°	1,008
C	150°	24	National Semiconductor	150°	1,000
C	175°	6	Signetics	175°	2,000
C	200°	6	Intel	200°	48

Source: [HITSTOR 1996]

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[11] Also known as Stabilization Bake.

3.2.4.2 Shock and Vibration

In non-operating conditions, shock and vibration are generally due to transportation and handling which is often much more severe than the actual use environment [C96-03 1996]. (Earlier in this document, Section 3.2.3.2 on page 16 covered shock and vibration requirements and tests.) Basic considerations when designing for shock include:

- the location of the component relative to the supporting structure,
- the orientation of the part with respect to the anticipated direction of the shock or vibration forces, and
- the method used to mount the part [Pecht and Pecht 1995, 66].

3.2.4.3 Corrosion

As discussed previously in Section 3.2.3.3 on page 19, moisture, high temperatures, and contaminants all accelerate corrosion. Exposure to contaminants such as sand or dust during non-operation depends on geographic factors as well as the actual building or shelter in which the electronics are stored. As with moisture, a product's hermeticity will determine the amount of contaminants that enter the product. Consequently, packaging (plastic vs. hermetic) and conformal coatings are crucial in non-operating as well as operating environments.

3.3 Commercial PEMs

A plastic-encapsulated microcircuit (PEM) consists of an integrated circuit chip physically attached to a leadframe, electrically interconnected to input-output leads, and molded in a plastic that is in direct contact with the chip, leadframe, and interconnects. A hermetically sealed microcircuit consists of an integrated circuit chip mounted in a metal or ceramic cavity, interconnected to the leads, and hermetically sealed to maintain a contact environment within the package.

Commercial and telecommunications electronics industries use PEMs, resulting in a large manufacturing base. With major advantages in cost, size, weight, performance, and availability, plastic packages have attracted 97% of the market share of worldwide microcircuit sales, although until recently MilSpecs prohibited their use. Prior to the 1980s, PEMS suffered from moisture-induced failure mechanisms such as corrosion, cracking, and interfacial delamination and temperature-induced failure mechanisms. In 1991, CALCE/EPRC observed no reliability differences between plastic-encapsulated and ceramic ICs tested at +85°C and 85% RH [CALCE 1991].

Today, high-quality, high-reliability, high-performance, and low-cost PEMs are common. CALCE/EPRC contends that hermetic packaging has not kept pace [PEM 1996]. Table 14 displays the advantages and disadvantages of PEMs relative to hermetic packages.

Table 14. Advantages and Disadvantages of PEMs

Advantages	Disadvantages
Potential lower cost in volume	Non-hermetic package
Greater variety of circuits & packages available	More limited temperature range
Mechanically more rugged	Higher thermal resistance
Lighter weight	More rigorous controls needed for board assembly
Higher packaging densities	More sensitive to internal thermal expansion stresses (die size dependent)
Thermal expansion coefficients closer match to most printed circuit boards	No universally accepted industry standards
More automated assembly methods	Absorbed moisture in surface mounted technology packages must be considered during assembly

Source: [Schultz and Gottesfeld 1994]

A recent study [Emerson et al. 1996, 3] evaluated the reliability and cost effectiveness of using PEMs in a typical military system, the Precision Lightweight Global Positioning System (GPS) Receiver (PLGR). The cost comparison indicated an average six-fold decrease in cost when commercial devices are used. Despite the harsh environmental conditions in which the system is expected to operate, assurance testing did not reveal any special problems with the commercial parts. Table 15 displays the worst-case design operating limits for the PLGR, which include exposure to low temperatures, moisture (humidity and immersion), and shock/vibration, although not high temperatures.

Table 15. PLGR Requirements

Environment	Requirement	Test Guidance
Temperature (operating)	-20°C to +70°C	MIL-STD-810E, Method 501.3, Proc. I & II
Temperature (non-operating)	-57°C to +70°C	MIL-STD-810E, Method 501.3, Proc. I & II
Humidity	RH 0% to 100% (non-precipitation)	MIL-STD-810E, Method 507.3, Proc. I
Vibration (*sine* wave)	1-inch double amplitude (5 to 7 Hz), 2.5g (7 to 40 Hz), 0.033-inch double amplitude (40 to 50 Hz), and 4.2 (50 to 500 Hz)	MIL-STD-810E, Method 514.4
Shock (general)	3 sawtooth 40 g shocks of 11 msec duration along x, y, z directions—a total of 18 shocks	MIL-STD-810E, Method 516.4, Proc. I
Shock (transit drop)	Drop on face, edge, and corner, 26 drops from a 48-inch height on a surface equivalent to floor of high mobility multi-purpose wheeled vehicle	MIL-STD-810E, Method 516.4, Proc. I
Salt atmosphere	5% solution salt fog for 48 hours	MIL-STD-810E, Method 509.3, Proc. I

Table 15. PLGR Requirements (Continued)

Environment	Requirement	Test Guidance
Immersion	Immersion in water to depth of 1 meter for 20 mins without leakage	MIL-STD-810E, Method 512.3
Fungus	Satisfies MIL-E-5400, paragraph 3.2.24.8	MIL-STD-810E, Method 508.4, Proc. IV

Source: [Emerson et al. 1996, 3]

An Air Force pilot program, Military Products from Commercial Lines, is redesigning the Communication, Navigation, and Identification avionics electronics components for the F-22 fighter aircraft and Commanche helicopter to make use of plastic instead of ceramic parts. According to the General Accounting Office [1996, 4], pilot program officials claim the redesigned modules can meet all the same functional requirements as the original design with the possible exception of one condition, a temperature requirement. However, they believe that additional analyses and tests will show that this condition can be successfully resolved.

The only military environments for which PEMs are not now recommended are environments requiring RHA microcircuits (see Section 3.2.3.4 on page 22) and long-term storage environments (see Section 3.3.1 on page 30) [Schultz and Gottesfeld 1995].

3.3.1 PEMs for Long-Term Storage

According to Tam [1995], demonstrating long-term dormant storage moisture reliability has become the last hurdle for PEMs. In 1995, the Navy [1995] expressed concern that PEM reliability may be unsatisfactory for long-term dormant storage systems, saying that hard data to support use of PEMs in the long term (15 to 20 years) is lacking and that accelerated life test data have not been correlated to PEM long-term storage reliability risks.

CALCE/EPRC took exception to this, saying that Texas Instruments conducted three separate studies involving six years of PEM moisture-life monitoring and assessment, testing of electrical characteristics under military temperature ranges, and assessing their robustness in moisture environments after the assembly process. The moisture reliability or average moisture lifetime of PEMs was assessed to correlate PEM capability in long-term storage.

Moreover, CALCE/EPRC studies [C96-31 1996] have been conducted in which both PEMs and ceramic packages that had been stored and operated for 10 to 15 years were examined for degradation. The PEMs did not show any appreciable degradation due to storage. In fact, the ceramic packages did not seem to be as rugged as the PEMs.

3.3.2 PEMs Research

IERI, CALCE EPRC, and AFRL have PEMs research projects related to operating and non-operating environments.

- IERI is undertaking a study to establish the efficiency of plastic encapsulation as compared with hermetic sealing techniques using autoclave testing [IERI 1997].
- A 1997 CALCE EPRC project [C97-03 1996] seeks to establish whether the rapid changes of altitude—when combined with temperature and humidity fluctuations experienced in fast jets—is an acceleration factor in the reliability equation for plastic encapsulated active devices. If so, it will determine the value of that acceleration factor. Four different surface mount package types from seven different manufacturers will be alternately exposed to high temperature, high humidity, and cold, low pressure, high altitude environments.
- In July 1994, AFRL and the U.S. Army Missile Command initiated a five-year research program to collect data on the use of PEMs in systems requiring long-term storage [Gilmour 1995].

CALCE EPRC has been researching the long-term storage on the operational reliability of PEMs in three areas: accelerated testing, degradation analysis, and assessing the life of intermittently used assemblies. Concerns were raised that exposure to elevated temperature/humidity will produce more corrosion in stored devices than in operating devices because stored devices lack the power dissipation to keep condensed moisture off the surface of the die. In response, CALCE EPRC's Project C96-24 [1996] conducted accelerated testing—including temperature cycling, highly accelerated temperature/humidity, and salt fog—to simulate the effects of long-term storage on PEMs. Of 100 parts that were exposed to 1,000 hours at +140°C, 85% RH, all 100 passed the post highly accelerated stress test (HAST) parametric testing. Project C97-01 [1996] continues this work, including an analysis of PEMs for use in the F-22.

Degradation analysis looks at the failure modes, failure sites, failure mechanisms, and the extent of degradation in PEMs stored for extended periods of time. Project C96-31 [1996] conducted assessments of the long-term reliability of electronic assemblies subjected to 10 to 12 years of dormancy, and found that the extent of degradation was very limited. The few instances of degradation were related to bond pad corrosion. No correlation between delamination and corrosion in parts fielded for 10 years or more was identified.

However, other tests have shown a correlation. Moreover, studies have shown that delamination at the top surface of the die can degrade the reliability of PEMs by increasing the shear stress on the wirebonds. This can lead to lifted ball bonds, broken wedge bonds, and sheared bond wires either immediately upon delamination or with repeated temperature cycling. In 1997, Project C97-04 [1996] will definitively determine if delamination is a serious reliability concern in electronic systems that have been fielded for several years and are now being certified for continued use.

Once the degradation has been characterized and potential failure sites, modes, and mechanisms identified, an assessment of "remaining life" can be derived, together with PoF-based acceleration transforms and future accelerated testing. In 1997, Project C97-02 [1996] is continuing the effort of Project C96-31 by examining the reliability of assemblies after extended intermittent use, a condition which is more severe than continuous use or storage alone. For example, the greatest potential for corrosion is for a duty cycle of 20% on - 80% off. In Project C97-07 [1996], CALCE/EPRC is developing a generic methodology for reliability growth in commercial assemblies that consists of both assessing the degradation in fielded assemblies and conducting accelerated tests to assess their remaining life.

3.4 New Reliability Assessment Methods

Given that the military needs to begin using commercial electronics parts, procedures are necessary to ensure the reliability of these parts for military applications. Reliability assessment methods that account for the entire life cycle of systems and that focus on root causes of failure are needed. A project at AFRL [Caroli 1995] is underway to investigate new methods of electronic system reliability assessment. Early results indicate that a large part of the reliability problem for electronic parts is due to deficiencies in requirements, design, manufacturing, and supplier quality. One of the approaches being evaluated is the PoF approach.

According to Pecht [1996, 12], the first step of PoF is to define and measure the operating and non-operating requirements of the military product. From this information, the thermal, mechanical, electrical, and electrochemical stresses acting on the product can be modeled. Then, stress analysis is combined with knowledge about the stress response of the selected materials and structures to identify

- where failure might occur (failure site),
- what form it might take (failure mode), and
- how it might take place (failure mechanism).

The time to failure for each potential failure mechanism is then calculated and the mechanism with the least time to failure is selected as the dominant failure site. From this information, it can be determined if the product will survive for its intended application life or if other measures need to be taken for increased robustness. These measures might include redesign or the use of special materials or manufacturing and assembly processes.

Several projects are using this approach to qualify commercial grade parts for military use. For example, AFRL's RELTECH program (see Section 3.2.1 on page 9) seeks to understand the performance and root causes of potential field failures for components, boards, and systems in diverse military/space environments, and to take proactive steps to reduce and eliminate these failures.

Similarly, CALCE/EPRC is developing a methodology [C97-05 1996] for uprating or upscreening of commercial parts for use in harsh environments whose conditions are beyond the manufacturer's ratings.

- The first task will be to determine the failure mechanisms that may occur in commercial grade parts when they are exposed to temperatures outside of the manufacturer's specified range. This will include not only catastrophic mechanical failure mechanisms but also the causes behind electrical parameter shifts that cause the device to operate outside of the manufacturer's datasheet limits.
- The next task will be to identify sources of data on the performance of parts outside of the specified temperature range. For this, CALCE will survey a number of leading device manufacturers and original equipment manufacturers to identify the types and amount of data they regularly collect.
- Then test procedures will be developed that can be used to determine the information necessary to evaluate the devices with respect to the previously identified failure mechanisms.
- Finally, several experiments will be conducted on typical parts to verify this methodology.

CALCE [1997] describes how CALCE/EPRC recently used this uprating methodology to assist AlliedSignal in deciding whether to substitute a commercial avionics microcontroller costing $19.00 for a hermetic ceramic one costing $560.00. In order to make the substitution, AlliedSignal and CALCE/EPRC defined a program for qualifying an industrial temperature range (-40°C to +85°C) microcontroller for use from -55°C to +125°C. Testing conducted on 100 microcontrollers indicated that the device would operate from -100°C to +160°C. Full parametric testing indicated that the device would remain within the manufacturer's electrical performance specifications from -70°C to +150°C. In addition, reliability degradation was not observed in any of the samples after exposure to the durability tests.

Another CALCE/EPRC project [C97-06 1996] will develop a set of criteria for the assessment of parts and the associated manufacturers of parts. Some of the initial work on this subject was presented in MIL-HDBK-179A as a means to enable the use of parts produced by companies employing commercial best practices. The C97-06 project will study device manufacturer processes, including qualification and continuous monitoring test methods, shipping and handling controls, and manufacturing process control methods to provide a benchmarking approach for the supplier to make parts management decisions. Deliverables to this study include a documented process and a set of criteria by which suppliers may assess "quality" parts and manufacturers. The basis will include but may not be limited to manufacturer process controls, qualification methods, continuous monitoring test methods, and shipping and handling controls. Various example cases of the process will be provided.

The Commercial Communications Technology Testbed is a joint project between the Defense Advanced Research Projects Agency and the Defense Information Systems Agency. Its purpose is to ruggedize commercial electronics to support mobile command and control requirements for battlefield use [C2T2 1995]. AFRL is developing a risk assessment program [DMS 1996] to identify those parts early on in the design process that are susceptible to becoming Diminishing Manufacturing Sources (DMS) candidates. The DMS program will help determine whether it is more cost effective to buy spares and store them or to redesign the board or system.

Appendix A.
Status of Reliability and Maintainability Specifications and Standards

In June 1994, Secretary of Defense William Perry initiated Military Specification and Standards Reform (MSSR) with his memorandum, *Specifications and Standards: A New Way of Doing Business.* The DOD conducted studies to identify standards in defense acquisitions that were barriers to commercial processes, as well as major cost drivers. This resulted in the compilation of the "105 Heartburn Specifications and Standards List." The Defense Standards Improvement Council (DSIC) was then formed to decide the fate of the documents on the list.

Table A-1 contains the Reliability and Maintainability standardization documents that appeared on the list with summaries of the final DSIC decisions. These decisions included cancelling some military standards, converting some to handbooks, and replacing some with non-government standards [Caroli and Gorniak 1995].

Table A-1. Reliability and Maintainability Standardization Reform

Document No.	Title	Current Plans
MIL-HDBK-217	Reliability Prediction of Electronic Equipment	Retain as a handbook. Issue a change notice clarifying that it is for guidance only. Cancel when IEEE or other organization develops a nongovernment standard replacement.
MIL-HDBK-338	Electronic Reliability Design Handbook	Retain as a handbook. Issue a change notice clarifying that it is for guidance only.
MIL-STD-470	Maintainability Program for Systems and Equipment	For short term, cancel by redesignating as a handbook. Consolidate with MIL-STD-471 and publish as a new handbook by June 1996.
MIL-STD-471	Maintainability Verification/Demonstration/Evaluation	For short term, cancel by redesignating as a handbook. Consolidate with MIL-STD-470 and publish as a new handbook by June 1996.
MIL-STD-690	Failure Rate Sampling Plans and Procedures	Planned for cancellation.

Table A-1. Reliability and Maintainability Standardization Reform (Continued)

Document No.	Title	Current Plans
MIL-STD-721	Definition of Terms for Reliability and Maintainability	Cancel. Contents will be retained in MIL-HDBK-338.
MIL-STD-756	Reliability Prediction and Modeling	Cancel. Contents will be retained in MIL-HDBK-338.
MIL-STD-757	Reliability Evaluation from Demonstration Data	Planned for cancellation.
MIL-STD-781	Reliability Testing for Engineering Development, Qualification, and Production	Cancelled after incorporating into MIL-HDBK-781A, 1 April 1996.
MIL-STD-785	Reliability Program for Systems and Equipment Development and Production	Cancel after publication of a suitable non-government standard. IEEE is presently working the standard. DSIC requested that IEEE attempt to publish the industry standard by June 1996.
MIL-STD-790	Reliability Assurance Program for Electronic Parts Specifications	Still active.
MIL-STD-810	Environmental Test Methods and Engineering Guidelines	Retain as a test method standard.
MIL-STD-883	Test Methods and Procedures for Microelectronics	Retain as a test method standard until a suitable nongovernment standard is available for use.
MIl-STD-1543	Reliability Program Requirements for Space and Missile Systems	Cancel after publication of a suitable non-government standard. This action will occur simultaneously with the replacement of MIL-STD-785.
MIL-STD-1629	Procedures for Performing a Failure Mode Effects and Criticality Analysis	Cancel after publication of a suitable non-government standard. The Society of Automotive Engineers (SAE) is presently working on the standard. DSIC requested that SAE attempt to publish an industry standard by June 1996.
MIL-STD-1635	Reliability Growth Testing	Planned for cancellation.
MIl-STD-2068	Reliability Development Tests	Planned for cancellation.
MIL-STD-2074	Failure Classification for Reliability Testing	Cancel. Contents will be retained in MIL-HDBK-338.
MIL-STD-2084	General Requirements for Maintainability of Avionics and Electronic Systems and Equipment.	Cancel via publication of a notice redesignating as a handbook.
MIL-STD-2164	Environmental Stress Screening Process for Electronic Equipment	Cancel via publication of a notice redesignating as a handbook.
MIL-STD-2155	Failure Reporting, Analysis and Corrective Action System (FRACAS)	Cancel via publication of a notice redesignating as a handbook.

Table A-1. Reliability and Maintainability Standardization Reform (Continued)

Document No.	Title	Current Plans
MIL-STD-2165	Testability Program Requirements	Cancel via publication of a notice redesignating as a handbook.
MIL-M-38510	General Specification for Microcircuits	Reclassified to Inactive for New Design in 1993. Superseded by Qualified Manufactures List (QML) document MIL-PRF-38535C, dated March 14, 1995.
MIL-H-38534	General Specification for Hybrid Microcircuits	Convert to a performance specification.
MIL-I-38535	General Specification for Integrated Circuits (Microcircuits) Manufacturing	Converted to a performances specification (MIL-PRF-38535D, 31 October 1995).

Source: Modified from [Caroli and Gorniak 1995]

List of References

[Army 1978] U.S. Army. 1978. *Storage Reliability of Missile Materiel Program, Storage Reliability Analysis Summary Report on Electrical and Electronic Devices.* Redstone Arsenal, Alabama.

[Autoclave 1996] *Autoclave Test.* 1996. The University of Maryland, Computer-Aided Life Cycle Engineering Electronics Packaging Research Center Defects Database Demo. Available at http://spezia.eng.umd.edu/general/demos/defects/ screens/autoclav.html.

[Barrett and Koch 1996] Barrett, R. and T. Koch. 1996. Accelerometer Installations in Extreme Industrial Environments. *Sound and Vibration* Vol. 30/No. 6: 20-26.

[BCC 1994] Business Communications Co., Inc. April 1994. *Conformal Coatings in the Global Electronics Industry.* John Feeney, author. GC-131R. Norwalk, CT.

[Bergmann 1996] Bergmann, Walter B. June 1996. *MilSpec Reform: Results of the First Two Years.* Washington, DC: Office of the Under Secretary of Defense for Acquisition and Technology, Acquisition Practices.

[Boeing 1994] Boeing Company. August 31, 1994. *The Boeing Company: An Overview.* Briefing. Seattle, WA.

[C2T2 1995] New Term Enters COTS Debate: "Rough and Ready." September 1995. *Military and Aerospace Electronics.*

[C95-18 1995] McClusky, P. 1995. *Use of Electronic Hardware at Elevated Temperature.* University of Maryland CALCE/EPRC Project C95-18. Available at http://spezia.eng.umd.edu/general/projects/summary/1996/c95-18.html.

[C96-03 1996] Barker, Donald. 1996. *New Shock and High G Loading Analysis.* University of Maryland CALCE/EPRC Project C96-03. Available at http://spezia.eng.umd.edu/general/projects/summary/1996/c96-03.html.

[C96-17 1996] Joshi, Yogi. 1996. *The Rationale and Requirements for Thermal Management and Analysis.* University of Maryland CALCE/EPRC Project C96-17. Available at http://spezia.eng.umd.edu/general/projects/summary/1996/c96-17.html.

[C96-24 1996] McCluskey, Pat. 1996. *Testing of PEMs for Long Term Storage Applications.* University of Maryland CALCE/EPRC Project C96-24. Available at http://spezia.eng.umd.edu/general/projects/summary/1996/c96-24.html.

[C96-25 1996] McCluskey, Pat. 1996. *Failure of Plastic Encapsulated Microelectronics at Low Temperature.* University of Maryland CALCE/EPRC Project C96-25. Available at http://spezia.eng.umd.edu/general/projects/summary/1996/c96-25.html.

[C96-31 1996] Pecht, Michael. 1996. *Experimental Degradation Analysis of Stored PEMs.* University of Maryland CALCE/EPRC Project C96-31. Available at http://spezia.eng.umd.edu/general/projects/summary/1996/c96-31.html.

[C97-01 1996] McCluskey, Pat. 1996. *Accelerated Testing of PEMs for Long Term Storage Applications.* University of Maryland CALCE/EPRC Project C97-01. Available at http://spezia.eng.umd.edu/general/projects/summary/1996/c97-01.html.

[C97-02 1996] McCluskey, Pat. 1996. *Experimental Degradation Analysis of Intermittently Used PEMs and Assemblies.* University of Maryland CALCE/EPRC Project C97-02. Available at http://spezia.eng.umd.edu/general/projects/summary/1997/c97-02.html.

[C97-03 1996] McCluskey, Pat. 1996. *Suitability of PEMs for Use in Fast Jet Avionics Systems.* University of Maryland CALCE/EPRC Project C97-03. Available at http://spezia.eng.umd.edu/general/projects/summary/1997/c97-03.html.

[C97-04 1996] McCluskey, Pat. 1996. *Effect of Delamination and Cracking on PEM Reliability.* University of Maryland CALCE/EPRC Project C97-04 Available at http://spezia.eng.umd.edu/general/projects/summary/1997/c97-04.html.

[C97-05 1996] McCluskey, Pat. 1996. *Uprating of Commercial Parts for Use in Harsh Environments.* University of Maryland CALCE/EPRC Project C97-05. Available at http://spezia.eng.umd.edu/general/projects/summary/1997/c97-05html.

[C97-06 1996] Pecht, Michael. 1996. *Criteria for Manufacturer Parts Assessment.* University of Maryland CALCE/EPRC Project C97-06. Available at http://spezia.eng.umd.edu/general/projects/summary/1997/c97-06.html, 1996.

[C97-07 1996] McCluskey, Pat. 1996. *Assessing the Remaining Life of Intermittently Used Assemblies.* University of Maryland CALCE/EPRC Project C97-07. Available at http://spezia.eng.umd.edu/general/projects/summary/1997/c97-07.html.

[C97-24 1997]	Dasgupta, Abhijit. 1997. *Assessment of High-Temperature, Fatigue-Resistant Solders.* University of Maryland CALCE/EPRC Project C97-24. Available at http://spezia.eng.umd.edu/general/projects/summary/1997/c97-24.html.
[CALCE 1991]	Computer Aided Life Cycle Engineering (CALCE). 1991. Endurance Testing of Ceramic vs. Plastic IC in High Temperature and Humidity Environment Yields Important Results. *CALCE News* (September). Available at http://spezia.eng.umd.edu/general/newsletter/news/9-1991.html.
[CALCE 1997]	Computer Aided Life Cycle Engineering (CALCE). 1997. CALCE EPRC and Member Company Share Uprating Success. *CALCE News* (January). Available at http://spezia.eng.umd.edu/general/newsletter/news/1-1997/front.html.
[Caroli 1994]	Caroli, Joseph. 1994. New System Reliability Assessment Methods. *Reliability Sciences Bulletin* Issue 20 (Fall/Winter 1994). Available at http://www-er.rl.af.mil/ER-News/20/system-rel.html.
[Caroli 1995]	Caroli, Joe. 1995. New System Reliability Assessment Methods Under Development. *Reliability Sciences Bulletin* Issue 22 (Fall/Winter). Available at http://www-er.rl.af.mil/ER-News/22/reform.htm.
[Caroli and Gorniak 1995]	Caroli, Joe and Mark Gorniak. 1995. Update: Reliability & Maintainability Standardization Reform. *Reliability Sciences Bulletin* Issue 22 (Fall/Winter). Available at http://www-er.rl.af.mil/ER-News/22/reform.htm.
[Charles and Hoffman 1993]	Charles, H. K. and E. J. Hoffman. 1993. Extreme Environments: Designing Packages for Space and Avionics. *Advanced Packaging* Vol. 2/No. 5: 10-14.
[Chen et al. 1990]	Chen, C. L., R.W. Johnson, and R. C. Jaeger. 1990. Multichip Thin-Film Technology for Low Temperature Packaging. *Electronic Components and Technology Conference* Vol. 1/No. 40 (May 23): 571-579.
[Condbaa 1997]	*Conductive Polymers in Electronics Manufacturing.* 1997. Electronics Manufacturing Productivity Facility. Available at http://empf.arl.psu/expertise/projects/condbaa.html.
[COTS 1995]	COTS Packaging Eyed for Military Avionics. 1995. *Military & Aerospace Electronics* Vol. 6/No. 2 (February): 4.
[Decker 1996]	Decker, Gilbert F. 1996. *Memorandum for Commander, U.S. Army Material Command on Policy Incorporating a Performance-Based Approach to Reliability in Request for Proposals (RFPs).* March 8, 1996. Available at http://spezia.eng.umd.edu/whats_new/newsbriefs/armpolcy.html.
[DMPG 1993]	*Assessment of Microelectronic Industrial Base: Final Report,* DoD Microcircuit Planning Group (DMPG). March 1993. Task Group Report.

[DMS 1996] Diminishing Manufacturing Sources. 1996. *Reliability Sciences Bulletin* Issue 23 (Spring/Summer). Available at http://www-er.rl.af.mil/ER-News/23/dms.htm.

[DSB 1993] Final Report: Commercialization Status Report and Progress Report on Implementing the Defense Science Board Recommendations. 1993. *Microelectronics* (October).

[Dussault 1995] Dussault, Heather. 1995. Single Event Anomalies in Avionics. *Reliability Sciences Newsletter* Issue 22 (Fall/Winter). Available at http://www-er.tl.af.mil/ER-News/22/single.htm.

[Duston et al. 1995] Duston, D., P. Rustan, and H. Garrett. 1995. COTS-Grade Electronics Set to Escape Earthly Bounds. *Military & Aerospace Electronics* Vol. 6/No. 12 (December): 23-25.

[Dylis and Ebel 1993] Dylis, D. D. and G. H. Ebel. 1993. *Vibration Failure of Aircraft Electronics.* Naval Surface Weapon Center. October 27. RAC/REF/28613-002.

[Emerson et al. 1996] Emerson, Douglas, Edward Hakim, and Anand Govind. 1996. *Plastic Encapsulated Microcircuit Reliability and Cost Effectiveness Study.* Army Research Laboratory. July. ARL-TR-939; DTIC no. AD-A 311 113.

[Fayette 1996] Fayette, David. 1996. Multichip Module (MCM) Reliability and Performance Assessment Program. *Reliability Sciences Newsletter* Issue 23 (Spring/Summer). Available at http://www-er.rl.af.mil/ER-News/23/mcm.htm.

[Featherston 1990] Featherston, R. E. 1990. Environmental and Safety Test Facilities at the Naval Weapons Center, China Lake. In *Proceedings of the IES*, 436-438.

[GAO 1996] U.S. Government Accounting Office. *Military-Commercial Pilot Program Offers Benefits but Faces Challenges.* June 1996. GAO/NSIAD-96-53.

[Gatzek 1961] Gatzek, L. E. 1961. Corrosion Problems Encountered in Silo Storage of Missiles. In *Proceedings of the IES*, 155-161.

[Gilmour 1995] Gilmour, Duane A. 1995. RL/MICOM PEM Storage Reliability Program, Rome Laboratory. *Reliability Sciences Bulletin* Issue 21 (Spring/Summer). Available at http://www-er.rl.af.mil/ER-News/21/storage.html.

[Guy 1995] Guy, John. May 1995. *Dealing with the Issues of Lead Solder Replacement.* Electronics Manufacturing Productivity Facility. EMPF-PP0011.

[HITSTOR 1996] *High Temperature Storage.* 1996. The University of Maryland CALCE/EPRC Defects Database Demo. Available at http://spezia.eng.umd.edu/general/demos/defects/screens/hitstor.html.

[IEEE 1993] Institute of Electrical and Electronics Engineers, Inc. 1993. *ANSI/ IEEE Std. 100-1992, The New IEEE Standard Dictionary of Electrical and Electronic Terms.* 5th ed. New York: IEEE.

[IERI 1997] The International Electronics Reliability Institute (IERI), Department of Electronic and Electrical Engineering, Loughborough University, United Kingdom. 1997. *Current Research Activity: Evaluation of Encapsulation Using Autoclave Testing.* Available at http://info.lboro.ac.uk/ departments/el/research/ieri/research/crrntres.html.

[Jackson 1996] Jackson, Margaret. 1996. *CALCE EPRC Conducts Survey in Response to Statements Made by National Semiconductor.* Available at http://spezia.eng.umd.edu/general/PEMs/nat-semi.html.

[Jones and Marsh 1992] Jones, W. M. and W. A. Marsh. 1992. Low-Temperature Environmental Determination Study of the Improved Tomahawk Ship-Launched Missile. In *Proceedings of the IES*, 332-340.

[Lau 1995] Lau, John H., editor. 1995. *Ball Grid Array Technology.* New York: McGraw-Hill, Inc.

[Lee 1962] Lee, C. B. 1962. Fungal Deterioration of Materiels in the Wet Tropical Environment of Panama. In *Proceedings of the IES*, 497-505.

[Livesay 1978] Livesay, B. R. 1978. The Reliability of Electronic Devices in Storage Environments. *Solid State Technology* (October): 63-68.

[McCluskey et al. 1997] McCluskey, F. Patrick, R. Grzybowski, and T. Podlesak. 1997. *High Temperature Electronics.* CRC Press, Inc.

[McGarry and Sisul 1977] McGarry, J. and E. Sisul. 29 April 1977. *Storage Reliability of Missile Material (Accelerated Testing of Patriot System Electronic Components).* McDonnell Douglas. DTIC no. AD-A 039 788.

[Malik 1976] Malik, D. F. May 1976. *Storage Reliability of Missile Material Program: Storage Reliability Analysis Summary Report. Volume I: Electrical and Electronics Devices.* Raytheon Co. LC-76-IC2.

[Malik et al. 1976] Malik, D. F., J. C. Mitchell, and R. E. Cordray. June 1976. *Reliability Prediction for Missiles (Dormant and Active).* Raytheon Co. LC-76-1. DTIC no. AD-A 026 104.

[MIL-HDBK-179A 1995] *MIL-HDBK-179A, Microcircuit Acquisition Handbook, Military Handbook.* 20 July 1995. Washington, DC: DOD.

[MIL-HDBK-781A 1996] *MIL-HDBK-781A, Handbook for Reliability Test Methods, Plans, and Environments for Engineering, Development, Qualification, and Production.* 1 April 1996. Washington, DC: DOD.

[MIL-PRF-38535D 1995] *MIL-PRF-38535D, Integrated Circuits (Microcircuits) Manufacturing, General Specifications for, Performance Specification.* 31 October 1995. Washington, DC: DOD.

[MIL-STD-883D 1991] *MIL-STD-883D, Test Methods and Procedures for Microelectronics.* 15 November 1991. Washington, DC: DOD.

[Moore 1995] Moore, Ben. 1995. *Electronics Cleaning Technology for 1996 and Beyond.* U.S. Air Force Rome Laboratory, Electromagnetics and Reliability. Available at http://www-er.rl.af.mil/ER-News/21/clean.html.

[Mshock 1996] *Acceleration/Mechanical Shock.* 1996. The University of Maryland CALCE/EPRC Defects Database Demo. Available at http://spezia.eng.umd.edu/general/demos/defects/screens/mshock.html.

[Navy 1995] *Response to U.S. Navy's Concern on the Use of PEMs.* 1995. University of Maryland CALCE/EPRC. Available at http://spezia.eng.umd.edu/general/PEMs/navy.html.

[Paulsen 1995] Paulsen, Brad. 9 February 1995. *Statement: National Semiconductor's Military and Aerospace Customers in Response to Motorola and AMD's Withdrawal from the Military/Aerospace IC Market.* National Semiconductor.

[Pecht 1996] Pecht, Michael. 1996. Why Traditional Reliability Prediction Models Do Not Work—Is there an Alternative? *Electronics Cooling* Vol. 2/No. 1 (January): 10-12.

[Pecht and Pecht 1995] Pecht, Judy and Michael Pecht. 1995. *Long-Term Non-Operating Reliability of Electronic Products.* CRC Press, Inc.

[PEM 1996] *PEM Encyclopedia.* 1996. University of Maryland CALCE/EPRC. Available at http://spezia.eng.umd.edu/general/demos/pem/chap1/1_0_0.html#intro.

[Perry 1994] Perry, William J. 1994. *Specifications & Standards: A New Way of Doing Business.* Memorandum. Washington, DC: U.S. Department of Defense. Available at http://www.acq.osd.mil/es/std/perry.htm.

[RAC n.d.] Reliability Analysis Center, U.S. Air Force Rome Laboratory. [n.d.] *Delphi Survey to Identify and Evaluate Reliability/Testability Approaches for VLSI Microcircuit-Based Systems Subjected to an Uncontrolled Storage Environment.* RAC/NORM/21480-000.

[RAC 1995] Reliability Analysis Center, U.S. Air Force Rome Laboratory. July 1995. *Benchmarking Commercial Reliability Practices.* RAC/IITRI/33878-000.

[Reid 1994] Reid, Kenneth J. 1994. *Automated Inspection/Solder Joint Inspection.* Electronics Manufacturing Productivity Facility. EMPF-PP0007.

[Rhea 1996] Rhea, J. August 1996. Shuttle Replacements's Avionics Going COTS. *Military & Aerospace Electronics* Vol.7/No. 8: 6, 10.

[Schultz and Gottesfeld 1994] Schultz, William L. and Sheldon Gottesfeld. September 8, 1994. *Reliability Considerations for Using Plastic-Encapsulated Microcircuits in Military Applications.* Melbourne, FL: Harris Semiconductor.

[Schultz and Gottesfeld 1995] Schultz, William L. and Sheldon Gottesfeld. 1995. Reliability Data Supports PEMS in Many Military Applications. *Military and Aerospace Electronics* Vol.6/No.1 (January).

[Seifert 1995] Seifert, Michael F. 1995. Electromagnetic Effects for Advanced Packaging. *Reliability Sciences Bulletin* Issue 22 (Fall/Winter). Available at http://www-er.rl.af.mil/ER-News/22/eme.htm.

[Sidharth and Barker 1996] Sidharth and Barker, D. B. 1996. Vibration Induced Fatigue Life Estimation of Corner Leads of Peripheral Leaded Components. *Journal of Electronic Packaging* Vol. 118 (December): 244-249.

[Solder 1997] Navy/BMP High Temperature Solders Project. 1997. University of Maryland CALCE/EPRC. Available at http://spezia.eng.umd.edu/trp/hitemp/hi-t-sol.htm.

[Sparling 1967] Sparling, R. H. 1967. *Corrosion Prevention/Deterioration Control in Electronic Components and Assemblies.* Redstone Arsenal, AL: U.S. Army Missile Command.

[Surfspec 1997] *Demand is Great for an Affordable Surface Spectroscopy System.* 1997. EMPF. Summary available at http://empt.arl.psu.edu/expertise/projects/surfspec.html.

[Tam 1995] Tam, S. 1995. Demonstrated Reliability of Plastic-Encapsulated Microcircuits for Missile Applications. *IEEE Transactions of Reliability* Vol. 44/No. 1 (March): 8.

[TEMPCYCL 1996] *Temperature Cycling.* 1996. The University of Maryland CALCE/EPRC Defects Database Demo. Available at http://spezia.eng.umd.edu/general/demos/defects/screens/tempcycl.html,

[THB 1996] *Temperature Humidity Bias Test.* 1996. The University of Maryland CALCE/EPRC Defects Database Demo. Available at http://spezia.eng.umd.edu/general/demos/defects/screens/thb.html.

[Venuti and Chin 1985] Venuti, K. and T. Chin. May 1985. *Conformal Coating Evaluation on Copper Circuitry.* Raytheon Co. BR-14929.

[Vuono and Crawford 1991] Vuono, Bill and Tim Crawford. April 1991. *Ultrasonic Cleaning of Military PWAs.* Electronic Manufacturing Productivity Facility. EMPF-TS0040.

[Walsh 1995] Walsh, Lois. 1995. 6.1 Basic Research on Device Reliability. *Reliability Sciences Bulletin* Issue 21 (Spring/Summer). Available at http://www-er.rl.af.mil/ER-News/21/basic.htm.

[Webster 1980] *Webster's New Collegiate Dictionary.* 1980. Springfield, MA: G.&C. Merriam Company.

[WQEC 1980]	Weapons Quality Engineering Center, Naval Undersea Warfare Engineering Station. 10 October 1980. *Underwater Vehicle Environments.* Keyport, WA. QE/K-80-454; DTIC no. AD-A 221 642.
[Zedro and Lamphear 1962]	Zedro, J. and A. Lamphear. 1962. Laboratory Simulation of Missile Flight Thermal Environments. In *Proceedings of the IES*, 309-313.

Glossary

autoclave testing	Measures resistance of plastic packages to moisture. The package is put in a chamber and subjected to superheated steam under pressure for a specified length of time.
automotive quality system	This system supports a high-volume customer base, addresses dominant failure mechanisms using qualified testing which includes MIL-STD-883, and includes both hermetic and plastic encapsulated parts.
ball grid array technology	For very high speed integrated circuits, solder-contact pads cover the entire bottom surface of the package in checkerboard fashion, not just around package periphery (as with chip carriers) [Lau 1995, 558].
Class M	The Defense Electronics Supply Center manages the standard microcircuit drawings and approves supply sources by accepting their certification of conformance to MIL-STD-883D requirements for these military electronic products [MIL-HDBK-179A 1995].
commercial (consumer) quality systems	This system produces products that invoke a wide spectrum of performance, quality, and reliability as they depend on the quality standards being applied by the company. Devices are offered almost exclusively in plastic packages for use in low-cost, large volume, benign consumer environments.
commercial (industrial) quality systems	This system produces products, hermetic or plastic packaged, to meet a particular industry specification. Specifications are restricted to a minimal supplier base, limiting business to those suppliers with the best quality record. These products are characterized by long-term quality and reliability and longer-term availability.
contact spiking	A failure mechanism, contact spiking is the penetration of metal into the semiconductor in contact regions.
corrosion	Chemical or electrochemical reaction of a metal with the surrounding environment [Webster 1980].
delamination	A separation between plies within the base material, or between the base material and the conductive foil, or both [Lau 1995, 568].

Dose-Rate and Internal Electromagnetic Effects	Caused by nuclear weapons threats. Effects include current and voltage transients, upset, latchup, snapback, and high dose rate burnout.
die attach	Process of attaching an integrated circuit chip (die) to a printed wiring board.
fine pitch components	Electronic components with very small distances between adjacent conductors.
hermetic packaging	Gastight enclosure (package) for a single element, an integrated or a hybrid circuit. Generally consists of a bottom part, called the case or header, and a top, called the cover or lid. These are sealed into one unit. [Lau 1995, 579, 590-591]
high density interconnect technology	A high-density multichip module approach developed by General Electric. The chips are mounted in cavities in a substrate. A polyimide film is laminated to the face of the chips and a laser is used to etch via holes for contact to the chip bonding pads. A thin-film multilevel interconnect structure is built on the polyimide overlay to interconnect the devices and input/output pads. [Lau 1995, 579]
dormancy	One of the two main non-operating environments. Dormancy is the state in which the equipment is in its normal operational configuration and connected, but not operating. (See **storage**.)
flux	In soldering, a material that chemically attacks surface oxides so that molten solder can wet the surface to be soldered, or an inert liquid which excludes oxygen during the soldering process [Lau 1995, 576].
J-leads	A surface-mount integrated circuit package whose leads are formed into a J pattern, folding under the device body [Lau 1995, 583].
lead	(1) That portion of an electrical component used to connect it to the outside world. (2) A conductive path, usually self-supporting. (3) A soft, heavy metal (chemical symbol *Pb*) that is used in solder compositions and other alloys.
Multichip module (MCM)	MCMs use advanced forms of printed wiring board technologies to form the copper conductors on plastic laminated-based dielectrics.
Neutron and Proton Damage	Caused by radiation belts, solar radiation, nuclear reactors, and nuclear weapons. Effects include gain degradation, increased noise, increased dark current for charge coupled devices, and secondary circuit effects from these.
Physics of Failure (PoF)	A reliability assessment methodology which includes an analysis of defects and failures; determination of root causes of problems; and, based on these analyses, recommends corrective actions in design,

	process, assembly, etc., to eliminate defects or failures. [MIL-HDBK-179A 1995, 7]
QML	Qualified Manufacturers' Listing is a list of manufacturers' facilities that have been evaluated and determined to be acceptable based on the test and approval of a sample specimen and conformance to the applicable specification in accordance with MIL-PRF-38535D.
Reliability	The ability of an item to perform a required function under stated conditions for a stated period of time [IEEE 1993, 1117].
rosin-based flux	A flux having a rosin base that becomes interactive after being subjected to the soldering temperature [Lau 1995, 599]
shock	A sudden change that affects the location, velocity, acceleration, or forces in a structure.
Single-Event-Effects (SEE)	The impact of galactic cosmic rays, solar enhanced particles and/or energetic neutrons and protons, and alpha particles. Effects include single-event-upset, single-event-latchup, single-event-burnout, single-event-gate-rupture, and single-event-hard-error.
slow trapping	A failure mechanism, slow trapping is the trapping of electrons when they cross the potential barrier of the silicon-silicon oxide interface, causing a shift in the threshold voltage.
surface charge spreading	A failure mechanism, surface charge spreading is the lateral spreading of ionic charge from biased metal conductors along the oxide layer or through surface moisture.
storage	One of the two main non-operating environments. Storage is the state in which the system, subsystem, or component is totally inactivated and resides in a storage area. (See **dormancy**.)
substrate attach	Process of attaching the substrate base material (substrate) of a hybrid to a printed wiring board.
THB testing	Temperature-humidity-bias testing under which electronic devices undergo a constant temperature, elevated relative humidity, and electrical bias (constant or intermittent, based on device type).
tin pest	Single-crystal growths resembling fine wire or whiskers occurring on boards or components that have been electroplated with tin. While humidity encourages the growth of these "whiskers," they are not caused by corrosion. Tin pest can cause electrical breakdown in circuits by bridging conductors. [Lau 1995, 611]
Total Ionizing Dose	Caused by radiation belts, solar radiation, nuclear reactors, and nuclear weapons. Effects include frictional failure, increased leakage and

	standby currents, timing degradation, and decreased I/O drive capability.
Via (hole)	An opening in the dielectric layer(s) of a multilayer structure, whose walls are made conductive to enable interconnections between conductive layers [Lau 1995, 609].
vibration	A periodic motion of the particles of an elastic body or medium in alternately opposite directions from the position of equilibrium when that equilibrium has been disturbed [Webster 1980].
void	The absence of substances in a localized area [Lau 1995, 610].

Acronyms and Abbreviations

AFRL	U.S. Air Force Research Laboratory (formerly Rome Laboratory)
C	Centigrade
CALCE/EPRC	Computer Aided Life Cycle Engineering/Electronic Packaging Research Center
CCA	circuit card assembly
CFC	chlorofluorocarbon
cm	centimeter
DCA	Direct Chip Attach
DESC	Defense Electronics Supply Center
DMS	Diminishing Manufacturing Sources
DOD	Department of Defense
DSB	Defense Science Board
DSIC	Defense Standards Improvement Council
DSPSE	Deep Space Program Science Experiment
DTIC	Defense Technical Information Center
ECS	Environmental Control System
EM	electromagnetic
EMPF	Electronic Manufacturing Productivity Facility
ERD	Electronics Reliability Division
ERS	Electronics Systems Engineering Division
F	Fahrenheit
FEA	Finite Element Analysis
FRACAS	Failure Reporting, Analysis and Corrective Action
g	gravity
GPS	Global Positioning System
HDI	High Density Interconnect
Hz	hertz
I/O	input/output
ICBM	intercontinental ballistic missile

IDA	Institute for Defense Analyses
IEEE	Institute of Electrical and Electronics Engineers, Inc.
IERI	International Electronics Reliability Institute
Krad	kilorad (1000 rads)
MCM	multichip module
MIL-PRF	Military Performance Specification
MIL-STD	Military Standard
MilSpecs	Military Specifications
MSSR	Military Specification and Standards Reform
NASA	National Aeronautics and Space Administration
NWE	Nuclear Weapon Environment
ODS	Ozone Depleting Sources
PEM	plastic-encapsulated microcircuit
PLGR	Precision Lightweight Global Positioning System Receiver
PoF	Physics of Failure
PWA	printed wiring assembly
PWB	printed wiring board
QML	Qualified Manufacturers' Listing
RAC	Reliability Analysis Center
RELTECH	Reliability to Achieve Insertion of Advanced Packaging
RH	relative humidity
RHA	radiation-hardness assurance
SAE	Society of Automotive Engineers
SEE	Single-Event-Effects
U.S.	United States
THB	temperature humidity bias
UV	ultraviolet

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13. ABSTRACT (MAXIMUM 200 WORDS)

In order to reduce costs and access the commercial industrial base, DOD is relaxing restrictions against using commercial grade electronics in military products. Are these commercial electronics devices adequate to meet the needs of defense products in hostile operating and non-operating environments for long periods of time? To help answer this question, this document looks at the ways in which electronics can fail and the specific requirements for electronics in military products. Manufacturing processes are responsible for many electronics failures. Other failures result from exposure to such stresses as temperature, humidity, vibration, shock, corrosion, radiation, and electricity during operation and non-operation.

This document describes each of these failure mechanisms, the military products that each affects, the tests that are used to qualify electronics parts, and research underway. It also presents several examples of situations where commercial electronics parts were used successfully in harsh environments whose conditions exceeded the manufacturer's ratings. New reliability assessment methods that focus on root causes of failure and dominant failure sites are essential to help engineers determine whether an electronics product will survive for its intended application life or if it needs to be redesigned. In particular, military requirements for high temperature and radiation hardness assurance pose special challenges for commercial electronics.

14. SUBJECT TERMS

Electronics, manufacturing, industry, defense, commercial, reliability, weapons systems, assessments, tests, specifications, microelectronics, plastic-encapsulated microcircuit (PEM).

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