CHAPTER 16
ELECTRONIC PACKAGING

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16.1 INTRODUCTION

16.1.1 Scope

Electronic packaging is a multidisciplinary process consisting of the physical design, product development, manufacture, and field support required to transform an electronic circuit into functional electronic equipment.

The categories of technical knowledge and design emphasis applicable to a given electronic product vary significantly in priority, depending on the intended product application (e.g., aerospace,

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automotive, computers, consumer goods, industrial equipment, marine equipment, medical equipment, military equipment, telephony, test equipment, etc.).

The key to successful electronic packaging is the ability to identify the applicable field of technology most likely to offer a solution to a design problem and then to apply that technology correctly in association with related technologies.

The focus in this chapter is on identification and categorization of the type of problem to be solved and selection of the most appropriate approach to that problem. For development of analytical solutions, detailed material properties, and appropriate manufacturing and assembly processes, the reader is referred to other chapters in this handbook, references at the end of this chapter, [1-3] or appropriate resources in each field.

The most important technical design considerations are listed below.

Component mounting techniques include mechanical, metallurgical, and adhesive techniques, which vary as a function of physical, thermal, and electrical interconnection requirements.

Fastening and joining techniques include threaded fasteners, rivets, welding, soldering, brazing, and adhesives utilized to mount and interconnect parts of an equipment, providing protection for contained circuit elements.

Interconnection techniques address the methods used to electrically interconnect passive and active circuit elements, including bonding, deposition, soldering, wiring, and connector systems.

Material selection techniques are used to identify and employ the most appropriate, cost-effective, and durable combination of materials for the intended product application.

Shock and vibration design practices offer methods to avoid product degradation from critical dynamic loads imposed in service.

Structural design of a system, enclosure, module, or bracket involves analytical, empirical, and experimental techniques to predict mechanical stresses. Included are thermal stresses, deformation under load, degree of enclosure, and RFI/EMI protection.

Thermal design includes the methods employed to control component temperatures to achieve satisfactory product reliability. Conduction, free and forced convection, radiation, liquid and evaporative cooling may be utilized within an equipment or between the equipment and the local environment.

Manufacturability of an electronic equipment depends on techniques to achieve ease of assembly, component selection, utilization of design rules consistent with manufacturing processes, and application of concurrent engineering and total quality management techniques.

Protective packaging includes the techniques employed to ensure that a product will survive handling, shipping, and storage environments without damage.

16.1.2 Overview

The design and analysis of electronic equipment consists of a hierarchical continuum, each level with similar yet varying characteristics. The goal is to provide the most favorable conditions for reliable operation of every component within an equipment. Working from the external environment inward:

1. *Exterior Conditions*. Service and storage environments define overall outer structural attachments, environmental conditions, electrical interconnection, power source, heat rejection, and ergonometric human factors requirements.
2. *Internal Conditions*. The equipment enclosure and structure provide mounting, thermal, and electrical interfaces between the outer environment and the internal environment, which contains electronic modules, subassemblies, and components.
3. *Component Environments*. Module and subassembly structures define the interface between individual electronic components and the equipment's internal environment.
4. *Component Requirements*. Components reside in modules and subassemblies and possess physical and operational characteristics defined by the component manufacturer and verified by test (temperature sensitivity, heat generation, mechanical stresses, shock and vibration fragility, operational life, assembly loads, reliability, mounting criteria, etc.).

Ongoing reductions in component sizes and power-dissipation levels will continue to compress equipment size and per-component thermal dissipation. Design emphasis will continue regarding addition of operational features, increased reliability, reduced maintenance, higher component density per unit volume, routing and wiring for very high-speed circuit operation, and reduction of production costs and schedules.

16.1.3 Design Techniques

Computer-based analysis and design environments and programs exist to aid with electronic packaging design and development tasks.[4] Most computer algorithms are adaptations of codes generated for other but related purposes (e.g., finite element techniques for structures and thermal analysis, fluid flow analysis and visualization, solid modeling and drafting programs, printed circuit board design programs, and others). In many instances, the underlying computational assumptions inherent in the program are not thoroughly documented.

There are several opportunities to introduce errors when building a predictive model of a product. The electronics packaging engineer must possess a basic understanding of each physical phenomenon and the underlying assumptions implicit in each type of analytical model as applied to the specific equipment under analysis.

16.2 COMPONENT MOUNTING

16.2.1 General

Components consist of any active (transistor, integrated circuit, display, disk drive, other) or passive (connector, wire, resistor, switch, heat sink, other) element mounted on or within electronic equipment. Components may require specific mounting techniques, such as socket-mounted relays, power transformers, heat sink or chassis-mounted semiconductor devices (Triacs, silicon-controlled rectifiers (SCRs), power transistors, other). Smaller electronic components (resistors, capacitors, integrated circuits, other) may be mounted to a rigid or flexible printed circuit board. Discrete components may be mounted either to a structure or to a printed circuit board.

16.2.2 Specific Components

Specific components include components and subassemblies that are not appropriate to printed circuit board mounting due to component size, special mounting needs, interconnection, serviceability, cost, or accessibility requirements.

Component-mounting techniques must be consistent with the requirements of each specific component. Component specifications provided by the manufacturer usually provide a guide to mounting requirements. Examples of specific components include disk drives (may require vibration-absorption mounting), liquid crystal displays (may require temperature control and avoidance of mechanical twist), power relays (vibration isolation and mechanical retention), panel-mounted switches and controls (environmental suitability and ergonometric considerations), connectors (strength, keying, and accessibility), and devices that generate significant amounts of heat.

16.2.3 Discrete Components

Discrete components are circuit elements not incorporated into an integrated circuit. Discrete components are mechanically attached to a structure, lead-soldered to electrical terminals, or soldered to a printed circuit board. Examples of discrete components include resistors and capacitors in leaded packages, individual transistors, rectifiers, bridges, relays, and light-emitting diodes (LEDs).

For the non-printed circuit board mounting of discrete components, a variety of mounting techniques are employed, depending on the detailed configuration of the discrete component to be mounted.

16.2.4 Printed Circuit Board Components

A printed circuit board consists of a substrate (usually FR4 glass epoxy) with a conductive layer (usually copper) that has been etched to reproduce a pattern of component mounting pads and interconnecting traces. A printed circuit board may be constructed of other substrates and circuit conductive materials to improve dissipation of heat and reductions in stresses due to thermal expansion between components and the substrate.

The printed circuit board[5] may have the etched circuit pattern on one side only or on both sides, with or without plated through-holes connecting the traces on either side of the board. Multilayer printed circuit boards offer additional planes of circuit trace patterns, with or without buried vias, to interconnect closely spaced multileaded components.

The use of increasingly smaller components and integrated circuits with greater internal complexity and high connection point counts of beyond 400 for an individual device forces ever-decreasing trace widths. Trace widths and spaces between traces of 0.010 in. or wider are common, as are fine-line board traces and spaces of from 0.010 to 0.006 in. Very fine-line boards from 0.006 in. to 0.001 traces and 0.002 spaces or smaller are difficult to achieve in production.

Flexible printed circuit boards constructed from thin polyester film substrates with copper conductors are fabricated in single, double, or multilayer format. With or without components attached, the flexible circuit board permits the shaping of a circuit to fit within an enclosure without the mechanical restrictions applicable to rigid circuit assemblies. Flexible printed circuits may be combined with rigid printed circuit boards to eliminate connectors and wiring harnesses by using the flexible circuits as interconnection between rigid board assemblies.

The various types of components mounted to a printed circuit board may be classified as either leaded components or surface-mounted components.

Leaded components are mounted by inserting component leads through holes in the printed circuit board and soldering the leads into place. Lead-trimming and board-cleaning operations follow. This technology is mature. Leaded components consist of discrete components and leaded integrated circuit (dual in-line package (DIP) with two rows of pins, and single in-line package (SIP)) packages.

A variation of leaded components is the pin grid array (PGA) package, where the integrated circuit is housed in a plastic or ceramic carrier and a matrix of pins extends from the bottom of the matrix for insertion into a printed circuit board. Such packages have pin counts up to 168 and higher.

Very large-scale integrated (VLSI) circuits[6] combine a multiplicity of circuit functions on an often custom-designed integrated circuit.

Surface-mount technology (SMT)[7] consists of attaching non-leaded packages to the printed circuit board by placing the components on patterns of conductors that have been coated with solder paste. Following placement, the assembly is heated to reflow the solder paste and bond the components to the printed circuit board.

Converting from a through-hole design to an SMT design usually reduces the printed circuit board area to about 40% of the original size. The area reduction is highly dependent on the specific components employed, interconnection, and mechanical considerations.

SMT components include:

- Small outline integrated circuits (SOIC), similar in appearance to DIP packages, except that the body of the component is smaller and the pins are replaced by gull wing or j-type lead configurations.
- Common SMT discrete package sizes known as 1206, 0805, 0603, and 0402 for resistors, capacitors and diodes; with EIA A, B, C, and D; and MELF packages for various types of capacitors.
- Plastic or ceramic leaded chip carriers (PLCC or CLCC), rectangular carriers with j-leads around all four edges. These components may be directly soldered to the printed circuit board or installed into a socket that in turn is soldered to the printed circuit board.
- Chip on board (COB), which consists of adhesive-bonding a basic silicon chip die to the printed circuit board, beam-welding leads from the die to the printed circuit board, and encapsulating the die and leads in a drop of adhesive potting compound.
- Ball grid array (BGA) packages, much like PGA packages, except that instead of an array of pins protruding from the bottom of the component, there is an array of solder balls, each attached to a pad on the component. The component may be either a plastic (PBGA) or a ceramic (CBGA) package. The BGA is placed onto a corresponding artwork pattern on the printed circuit board and the assembly is subjected to heat to reflow the solder balls, thus attaching the BGA to the printed circuit board.
- Flip chip package, a component package manufactured with small solder balls placed directly on the circuit substrate where electric connections are required. The substrate is then "flipped" or turned over so that the solder balls may be fused by reflow directly to pads on a printed circuit board.
- Multichip module (MCM), a component package, houses more than one interconnected silicon die within a subassembly. The subassembly is then attached to a printed circuit board as a through-hole or SMT component. In one manifestation, the MCM is a SIP circuit board mounted to the main printed circuit board assembly.
- Silicon on silicon (SOS), a component package consisting of silicon die attached to a silicon substrate to create a custom integrated circuit assembly. The subassembly is attached to the printed circuit board like a conventional component.

16.3 FASTENING AND JOINING

16.3.1 General

Fastening and joining techniques are used to achieve mechanical assembly of the electronic equipment. Fastening may involve attachment of the electronic product into its use environment, fabrication of the product mechanical structure, attachment of subassemblies, modules, or printed circuit boards into the equipment, attachment of a specific component, or attachment of a discrete component to a structure or printed circuit board. In each case, the fastening requirements are different and must be evaluated for each specific application.

16.3.2 Mechanical Fastening

Conventional machine design techniques apply to the design of mechanical joints employing threaded fasteners, rivets, and pins. These techniques are employed when strength and deflection are the design criterion; for example, attachment of an electronic equipment to its host structure and attachment of specific components to the structure of the electronic equipment. Dynamic loads (shock and vibration) require additional consideration, as does selection of fastener materials to avoid corrosion.

In many mechanical fastening applications within an electronics equipment, strength is not an issue and fastener size is selected based on the need to reduce the number of screw sizes (cost issue) and the space available for mechanical fastening. In these cases, for commercial applications where corrosive environments are not a significant issue, cadmium-plated fasteners are employed. For instances where dissimilar metal fastener and component parts are exposed to moisture or corrosive environments, stainless steel fasteners are advised.

Screw head selection is important in electronic equipment applications. Phillips-head screws are preferred over slotted head screws due to their ability to gain increased tightening torque. Pan-head screws are preferred over round-head screws due to their absence of sharp edges. Flat-head screws are used to hide the screw head within the material thickness of one of the structural elements; however, there is no allowance for tolerances that exist between flat-head screws in a multifastener joint.

When threaded fasteners are used, there is concern that the joint will loosen and become ineffective over time. Such loosening may be caused by thermal cycling or vibration. It is necessary to ensure that the threaded joint maintains strength. Techniques to prolong threaded joint integrity include:

- Using a lock washer between the nut and the base material, or under the screw head if the nut is part of or pressed into the base material. If a nut is used, place a flat washer between the lock washer and the base material to avoid damage to the base material.
- If an electrical bond must be established through the threaded joint, a tooth-type lock washer without a flat washer must be employed.
- Using a compression nut (formed to cause friction between the nut and the screw threads). This device loses effectiveness if frequently removed and may require replacement.
- Using a nut or screw with a compressible insert. This applies to screw sizes of #6 and larger. The same warning on reuse applies as for the compression nut.
- Using a screw-retention adhesive material on the threads prior to making the joint. The adhesive must be reapplied each time the joint is disassembled. Various degrees of hold are available.
- Using anti-rotation wire through a hole in the nut or in the head of the screw. Applicable to larger bolts only.
- Tooth-type lock washers should not be used in contact with printed circuit board or other nonmetallic materials.
- Joints where one or more elements are capable of cold flow, e.g., nylon, plastics, and soft metal, require a retention method other than compression-type lock washers.

Rivets used in electronics assembly may be solid or tubular. Do not depend on a riveted joint to provide long-term electrical connectivity. Cold flow will lead to joint looseness when plastic materials are involved. Rivet material must be compatible with other materials in the joint to avoid corrosion.

Pins pressed into holes in mating parts are sometimes used to make permanent joints. Pin joints may be disassembled, but a larger-diameter pin may be required to achieve full joint strength upon reassembly. Materials selection is important to avoid corrosion.

16.3.3 Welding and Soldering

Conventional spot welding, inert gas welding, torch welding, and brazing[8] are used in the construction of metal chassis and other structural components. Such joints have consistent electrical conductivity. Material properties in the heat-affected zone are often altered and may cause mechanical failure. Lap joints must be cleaned and protected from ingestion of contaminates, which may eventually cause corrosion, loss of electrical conductivity, and mechanical failure of the joint.

Lead–tin solder is used to make electrical joints[9–11] and is the material that binds components to printed circuit boards. Eutectic 63% lead/37% tin solder has a relatively low melting point and is used for attachment of components to circuit boards. Sixty percent lead/40% tin solder is commonly used for cable and connector applications. Special alloy solders contain other metals, such as silver, for applications where standard solder may leach away material from electroplated contacts.

In applications where a soldered electrical joint is needed and mechanical stresses will be present, the joint must be designed to accept the mechanical stresses without the solder present. Under load, a solder joint will creep until the loads are eliminated or the joint fails. As a result, solder is generally used only for electrical connection purposes and not for carrying mechanical loads.

Solder is the only means of mechanical and electrical support for surface-mounted parts on a circuit board assembly. Successful surface-mount design requires that the mass of the individual parts be very small and that the circuit board be protected from bending stresses so that attachment points will not eventually fail due to creep or fatigue fracture. Due to variances in the coefficient of thermal expansion between the circuit board substrate and the component materials, solder joints will be subjected to thermal cycling-induced stresses caused by environmental or operationally generated temperature changes.

16.3.4 Adhesives

Adhesives[12] are used in electronic equipment for a variety of purposes, such as component attachment to circuit boards in preparation for wave soldering, encapsulants used to encase and protect components and circuits, and adhesives used to seal mechanical joints to avoid liquid and gas leakage.

Adhesive joints withstand shear loads, but are much weaker when subjected to peeling loads. The load-bearing properties of cured adhesive joints (creep, stiffness, modulus of elasticity, and shear stresses) may vary significantly over temperature ranges often experienced in service. Successful joints using adhesives are designed to bear mechanical loads without the adhesive present, with the adhesive applied to achieve seal.

Adhesives may release chemicals and gases that are corrosive to materials used in construction of electronic components. Such adhesives must be avoided or fully cured prior to introduction into a sealed electronic enclosure.

16.4 INTERCONNECTION

16.4.1 General

Interconnection techniques are used to electrically connect circuit elements and electronic assemblies. Different design criteria apply to the various levels of interconnection. The categories of interconnection are as follows.

16.4.2 Discrete Wiring

Discrete wiring involves the connection from one component to another by use of electronic hookup wire, which may either be insulated or uninsulated. In either case, the individual connections are made by mechanically by forming the component leads to fit the support terminals prior to applying soldering to the connection. Care is taken to route wires away from sharp objects and to avoid placing mechanical stresses on the electrical joints.

16.4.3 Board Level

Board-level interconnection is accomplished by soldering components to a conductive pattern etched into the printed circuit board. Panel- or bracket-mounted parts may require discrete wiring between the component and the printed circuit board. Board assemblies sometimes consist of two or more individual circuit boards where a smaller board assembly is soldered directly to a host circuit board.

Socket-type connectors may be soldered to a circuit board to receive integrated circuits, relays, memory chips, and other discrete components. Care is exercised to ensure that the socket provides mechanical retention of the part to prevent the part from being dislodged by transportation and service environments.

16.4.4 Intramodule

Discrete components and circuit board assemblies located within an electronic subassembly, or module, are interconnected within the module. In addition, the module circuits and components are presented to an interface, such as one or more connectors, to facilitate interconnection with other modules or cable assemblies.

16.4.5 Intermodule

Individual modules are interconnected to achieve system-level functions required of the equipment of which they are a part. Modules may plug together directly using connectors mounted to each module, be interconnected by cable and wiring harness assemblies, or plug into connectors arrayed on a common interconnection circuit board sometimes called a "mother" board.

16.4.6 Interequipment

System-level interconnection between electronic equipment may consist of wiring harness assemblies, fiber-optic cables, or wireless interconnection.

16.4.7 Fiber-Optic Connections

Fiber-optic[13] links are sometimes employed instead of conventional metallic conductors to interconnect electronic systems. Fiber-optic communications consists of transmitting a modulated light beam through a small-diameter (100 micrometers) glass fiber to a receiver, where the modulated light signal is transformed to an electrical signal. Used extensively in communications, fiber-optic links are valuable for transmitting information but cannot carry electrical current. Design is centered on methods to provide connectors and splices without inducing signal reflection and attenuation. The design must accommodate minimum bend radii, which are a function of the number of fibers in a cable, and the fibers must be supported to avoid excessive mechanical stresses.

16.5 MATERIALS SELECTION

16.5.1 General

Electronic equipment enclosures, structure, and internal mounting brackets and devices are fabricated from a variety of materials. Materials selection consists of employing the materials that have the required physical properties, are suitable when used in combination with other materials, and may be fabricated.

16.5.2 Materials

A wide variety of materials are used in electronic packaging. Key considerations are strength, electrical conductivity, thermal conductivity, thermal coefficient of expansion, and manufacturability. Materials range from electrically conductive (used to conduct signals) to non-conductive (electrical insulators), and include ferrous (iron-bearing) metals, non-ferrous metals, plastics, ceramics, and glasses. Materials are selected based on the requirements of the intended application. The electronics packaging engineer is often required to use components where the component materials selection was determined by the component manufacturer. Such component materials must be identified and often require protection to assure maximum component life.

16.5.3 Metals

A variety of metals[14] are used in electronic equipment. Their properties are well documented in printed and electronic database files. Metals commonly encountered and used in electronic packaging include both non-ferrous[15] and ferrous[14] alloys.

16.5.4 Plastics and Adhesives

Several families of plastics[16,17] are used in electronic equipment, with family member variations formulated to solve very specific problems. Adhesives used in electronic packaging[12] are often found as subsets of plastic family members (e.g., epoxy adhesives). Individual manufacturers of plastics sometimes focus on a given family. The properties of plastic family members are found in lists and databases that address the family of plastics under consideration.

16.5.5 Ceramics and Glasses

Ceramic materials[18,19] are commonly employed in electronic components, less commonly in design of electronic equipment due to brittleness and sensitivity to mechanical bending and shock loads. Ceramics are used as incompressible electrical insulators,[20] which may be formulated to conduct heat away from critical components. Glass applications include semiconductor manufacturing (silicon die) and as a sealing material between metal and ceramic parts.

16.5.6 Corrosion

Corrosion is the result of an electrochemical reaction where metals ranking at different levels on the electrogalvanic chart are in the presence of an electrolyte. This situation is similar to that in a storage cell, where the anodic element suffers sacrificial deterioration. Corrosion failures may manifest themselves as loss of electrical conductivity or loss of strength in a joint. In some metals, corrosion leaches elements from grain boundaries and leads to weakened structural properties. Corrosion may occur at interruptions in the plating that expose the base metal to which the plating is applied.

Methods to control corrosion[16] include selection of materials with least offset in the galvanic series, use of electrical insulators between metals to break the current path from anode to cathode, and protection against the introduction of electrolytes.

16.6 SHOCK AND VIBRATION

16.6.1 General

Shock and vibration[21] loads consist of implusive and repetitive mechanical forces acting on an equipment.

16.6.2 Environmental Loads

Sources of shock loads include objects striking an equipment, structural-borne stress waves such as those caused by gunfire recoil, the equipment falling and striking other objects, and forces induced by handling and shipment.

Vibration sources include motion induced by rotating machinery, aerodynamic or hydrodynamic buffeting, and motion caused by usage and transportation.

16.6.3 Life

Equipment life is reduced by shock loads, which fracture components and cause catastrophic breakage or deformation. Fatigue and wear failures result from vibration-induced or other repetitive stresses that produce incremental damage that accumulates until failure occurs.

16.6.4 Shock

Shock is a sudden change in momentum of a body. A shock pulse may range from a simple step function or haversine pulse to a brief but complex waveform composed of several frequencies. The shock pulse may result in bending displacement and subsequent (ringing) vibration of the equipment or elements thereof. Shock pulses of a duration near the fundamental or harmonic of the resonance of the structure often cause greatly magnified and destructive responses. Shock failures include:

1. Permanent localized deformation at point of impact
2. Permanent deformation within an equipment if structural elements such as mounting brackets are deformed or fractured
3. Secondary impact failures within an equipment should structural deformations cause components to strike adjacent surfaces
4. Temporary or permanent malperformance of an operating equipment
5. Failure of fasteners, structural joints, and mounting attachment points
6. Breakage of fragile components and structural elements

Design techniques employed to avoid shock-induced[7,22] damage include:

1. Characterization of the shock-producing event in terms of impulse waveform, energy, and point of application
2. Computation or empirical determination of equipment responses to the shock pulse in terms of acceleration (or "g" level) vs. time
3. Modification of the equipment structure to avoid resonant frequencies that coincide with the frequency content of the shock pulse
4. Assuring that the strength of structural elements is adequate to withstand the dynamic "g" loading without either permanent deformation or harmful displacements due to bending
5. Selecting and using components that are known to withstand the internal shock environment to which they are subjected when the local mounting structure responds to the shock pulse
6. Employing protective measures such as energy absorbing or resonance modifying materials between the equipment and the point of shock application, or within the equipment to mount fragile components

16.6.5 Vibration

The response of an equipment to vibration can be damaging if the equipment or elements thereof are resonant within the pass band of the excitation spectra. Vibration failures include:

1. Fretting, wear, and loosening of mechanical joints, thermal joints and fasteners; and within components such as connectors, switches, and potentiometers
2. Fatigue-induced structural failure of brackets, circuit boards, and components
3. Physical and operational failures should individual structural element bending displacements produce impact with adjacent objects
4. Deviations in the performance of electronic components caused by relative motion of elements within the component or by the relative motion between a component and other objects

Design techniques employed to avoid vibration-induced damage include:

1. Characterization of the energy and frequency content of the source of vibration excitation
2. Analytical and empirical determination of equipment primary, secondary structural responses, and component sensitivity to vibration excitation in the pass band of the source vibration
3. Control of individual resonance response frequencies of an equipment structure and internal elements to avoid coincidence of resonance frequencies
4. Employment of materials that have adequate fatigue life to withstand the cumulative damage predicted to occur over the life of the equipment
5. Use of energy-absorbing materials between the equipment and the excitation source, and within the equipment for the mounting of sensitive components

16.6.6 Testing

The primary purposes of testing related to shock and vibration are to verify and characterize the dynamic response of the equipment and components thereof to a dynamic environment and to demonstrate that the final equipment design will withstand the test environment specified for the equipment under evaluation.

Basic characterization testing is usually performed on an electrodynamic vibration machine with the unit under test hard-mounted to a vibration fixture that has no resonance in the pass band of the excitation spectrum. The test input is a low-displacement-level sinusoid that is slowly varied in frequency (swept) over the frequency range of interest. Sine sweep testing produces a history of the response (displacement or acceleration) of selected points on the equipment to sinusoidal excitation over the tested excitation frequencies and displacements.

Caution is advised when using a hard-mount vibration fixture, as the fixture is very stiff and capable of injecting more energy into a test specimen at specimen resonance than would be experienced in service. For this reason, the test input signal should be of low amplitude. In service, the reaction of a less stiff mounting structure to the specimen at specimen resonance would significantly reduce the energy injected into the specimen. If a specimen response history is known prior to testing, the test system may be set to control input levels to reproduce the response history as measured by a control accelerometer placed at the location on the test specimen where the field vibration history was measured.

Vibration-test information is used to aid in adjusting the equipment design to avoid unfavorable responses to the service excitation, such as the occurrence of coupled resonance (e.g., a component having a resonance frequency coincident with the resonance frequency of its supporting structure; or structure having a significant resonance which coincides with the frequency of an input shock spectrum). Individual components are often tested to determine and document the excitation levels and frequencies at which they malperform. This type of testing is fundamental to both shock and vibration design.

For more complex vibration-service input spectra, such as multiple sinusoidal or random vibration spectra, additional testing is performed, using the more complex input waveform on product elements to gain assurance that the responses thereof are predictable. The final test exposes the equipment to specified vibration frequencies, levels, and duration, which may vary by axis of excitation and may be combined with other variables such as temperature, humidity, and altitude environments.

16.7 STRUCTURAL DESIGN

16.7.1 General

Structural design of a system,[22–24] equipment structure, module structure, or bracket involves analytical, empirical, and experimental techniques to predict and thus control mechanical stresses.

16.7.2 Strength

Strength is the ability of a material to bear both static (sustained) and dynamic (time-varying) loads without significant permanent deformation. Many non-ferrous materials suffer permanent deformation under sustained loads (creep). Ductile materials withstand dynamic loads better than brittle materials, which may fracture under sudden load application. Materials such as plastics often exhibit significant changes in material properties over the temperature range encountered by a product.

Many equipment require control of deflection or deformation during service. Such structural elements are designed for stiffness to control deflection but must be checked to assure that strength criteria are achieved.

16.7.3 Complexity

An equipment is viewed as a collection of individual elements interconnected to achieve an overall systems function. Each element may be individually modeled; however, the equipment model becomes complex when the elements are interconnected. The static or dynamic response of one element becomes the input or forcing function for elements mounted to it.

The concept of mechanical impedance[25] applies to dynamic environments and refers to the reaction between a structural element or component and its mounting points over a range of excitation frequencies. The reaction force at the structural interface or mounting point is a function of the resonance response of an element and may have an amplifying or damping effect on the mounting structure, depending on the spectrum of the excitation. Mechanical impedance design involves control of element resonance and structure resonance, providing compatible impedance for interconnected structural and component elements.

16.7.4 Degree of Enclosure

Degree of enclosure is the extent to which the components within an electronic equipment are isolated from the surrounding environment.

For vented enclosures, the design must provide drain holes to facilitate elimination of induced liquids and condensation. Convection-cooled equipment used in environments with airborne particles may require filtration. Equipment cooled by forced air usually require filtration on air inlets.

Completely (hermetically) sealed equipment enclosures using metal or glass seals permit the internal humidity and pressure to be defined when the unit is sealed. It is necessary to control the dryness of internal gases to protect from condensation, induced corrosion and to assure that internal pressures due to heating in combination with external ambient pressures (e.g., due to altitude changes) do not exceed structural deformation limitations and stress capabilities of the enclosure.

Partially sealed enclosures using permeable sealing materials (e.g., adhesives and plastics, etc.) are vulnerable to penetration by water vapor and other gases. Pachen's law states that the total pressure inside an enclosure is the sum of the partial pressures of the constituent gases. When the external partial pressure of a constituent gas is higher than the internal partial pressure of that gas, regardless of the total pressure inside the equipment, the gas will permeate the seal until the internal and external partial pressures are equalized. When the gas is water vapor and is ingested into an equipment, condensation will occur during temperature cycles, resulting in corrosion and perhaps interruption of electrical signals. Permeable seals do not protect from internal moisture damage and corrosion.

Equipment that operate in the presence of explosive gases must incorporate components that cannot cause ignition, and exposed circuits must operate at low voltage and current conditions so that short-circuit heating is controlled or eliminated. Vented equipment require use of flame-propagation barriers, such as screen mesh, that demonstrate under test that should ignition occur inside the unit, the flame front will not propagate into the outer environment.

16.7.5 Thermal Expansion and Stresses

The coefficient of thermal expansion is a material property and varies widely among the materials used in the construction of an electronic equipment. When bonded or fastened together and subjected to temperature changes, materials with different coefficients of thermal expansion cause bending and shear stresses that may be detrimental to the operation or life of an equipment.

Thermal cycling of bonded elements leads to failure, such as loss of electrical contact between bolted joints, cracking and breaking of ceramic parts bonded to plastic or metal surfaces, and solder joint failure. Thermal stresses are reduced by selecting adjoining materials with the least difference in coefficient of thermal expansion.

16.8 THERMAL DESIGN

16.8.1 General

The object of thermal design[26,27] is to control component temperatures to achieve satisfactory product reliability.[28] Component-fabrication techniques, such as complementary metal oxide semiconductor (CMOS), greatly reduce power requirements and component heat generation. Continuing reductions in equipment size lead to increased component density and power generated per unit volume. Thus, even when an equipment employs low-power components, thermal design practices must be applied.

Thermal design hierarchy includes:

1. Equipment total heat generation and how that heat will be dissipated to the local external environment
2. Equipment internal environment, which is the environment experienced by modules, subassemblies, and components
3. Control of critical component temperatures

Thermal design also includes consideration of temperature sensitivity of materials, finishes, adhesives, and lubricants.

Heat flow and temperature are analogous to current and voltage. *Thermal resistance* (in °C per watt) relate temperature to the flow of thermal energy in the same manner as Ohm's law relates voltage to the flow of electrical current.

Thermal resistances are used to characterize heat flow through a material, components such as heat sinks, interfaces between components and mounting surfaces, interfaces between structural elements and joints, and interfaces between the equipment and the local external environment.

Thermal design includes definition of heat flow paths from the component to the ultimate heat sink and, for each heat flow path, the identification and selection of thermal resistances that ensure that component temperatures are maintained at acceptable levels.

16.8.2 Heat Transfer Modes

Conduction

Conduction is the transfer of thermal energy through a material medium, which may be solid, liquid, or gas. Conduction of heat from a source to the ultimate heat sink includes, as appropriate:

1. Component internal heat transfer from heat source to the component interface with local air and mounting surfaces. Component specifications usually include a thermal resistance, which relates an internal critical point temperature (such as a semiconductor junction) to a specified location on the component package.
2. Contact resistance between the component and its mounting surface. Contact resistance depends on contact area, pressure (over time), and presence of thermal grease or other materials used to lower contact resistance. Contact resistances are often defined experimentally.
3. Thermal conduction through structural elements is defined in tables of material properties as the coefficient of thermal conductivity.
4. Interface resistances due to structural joints, often defined experimentally.
5. Thermal resistance of heat sinks[29] used to dissipate energy to gas or liquid coolants. Conduction heat sinks include liquid-cooled cold plates, convection heat sinks, evaporative devices such as heat pipes, and thermoelectric (Peltier effect) cooling devices.

Free Convection

Free convection involves the rejection of thermal energy to air or gases surrounding a component or equipment in the absence of mechanically or environmentally induced motion of the gases. Free convection is a continuing process where the warming of gases in immediate contact with a warm body produces natural buoyancy and movement of the heated gases away from the warm object. Cooler gases are drawn toward the warm body, replacing the escaping warm gases.

Free convection thermal resistances depend on orientation of warm surfaces relative to gravity, surface area, and surface finish. Free convection is enhanced by extended surfaces,[29] such as fins, to increase the effective contact area between the warm surface and local gases. Manufacturers of commercial heat sinks provide thermal-resistance information.

Equipment cooled by free convection require venting to permit the escape of warm gases and entrance of cooler gases. Warm components must be in the flow path of the cooling gases and internal obstructions must be avoided that would impede flow of the cooling gases.

Natural convection cooling is a mass rate of flow process, and cooling effectiveness is decreased by reduction in ambient air pressure (thus lowering the density of the cooling gas) such as occurs at higher altitudes.

Forced Convection

Forced convection may be produced mechanically with fans and blowers, by the result of equipment movement during use, or by naturally occurring air movement (wind) over unsheltered equipment. Forced convection thermal resistances are much lower than thermal resistances effected by natural convection cooling.

Forced-convection cooling air is first ducted to the most temperature-sensitive components, with less sensitive components located downstream, based on temperature sensitivity.

Forced-convection heat sinks[30] are often used to cool primary heat dissipation components and assemblies.

Forced-convection thermal resistance is sensitive to the mass rate of flow and velocity of the cooling air. Mass rate of flow is pressure-dependent and decreases with reductions in ambient pressure. Decreased mass rate of flow causes increases in thermal resistance. Increased air velocity past the cooled object reduces the thickness of the boundary layer and decreases the thermal resistance, creating improved cooling.

Radiation

Radiation is the transfer of energy from a warmer object to a cooler object by infrared radiation. Unlike convection cooling, radiation heat transfer occurs in vacuum and is not dependent upon the presence of gaseous media between the objects.

The effectiveness of radiation heat transfer is dependent on the temperature differential between the objects, the distance, the projected area, and the emissivity of the emitting and receiving surfaces. Radiation cooling (or heating) is reduced if smoke or other particulate matter is suspended in intervening gases.

Radiation is the primary mode of heat transfer in outer space. However, unless large temperature differences and short separation distances are experienced between earthbound objects, radiation involves a small fraction of the total heat flow.

Solar radiation causes heat buildup when ultraviolet rays (radiated from a high-temperature source) strike the surface of a closed equipment case, thus adding to the heat load within the equipment. Should solar radiation pass into a device, as through plastic or glass that is transparent to ultraviolet rays, the radiation will heat internal surfaces, which will then radiate at infrared frequencies to which the transparent material is usually opaque. In this way, thermal energy is trapped inside the enclosure and may lead to excessive internal temperatures. Solar panels make use of this phenomenon to heat water and living spaces. Solar-induced heat loading must be considered whenever electronic equipment is exposed to the sun.

Evaporation

Evaporation cooling and condensation techniques utilize the latent heat of vaporization of a heat transfer liquid, such as water, alcohol, freon, or other liquid, to effect temperature control. Thus, when an object is submerged within a liquid, the temperature of the object is controlled to the boiling point of the liquid (100 °C for water) within which it is submerged.

Heat pipe and evaporation chamber devices utilize evaporation by containing a liquid and providing an internal capillary structure to return condensed liquid from the cool end of the device to the heated end of the device.

16.9 MANUFACTURABILITY

16.9.1 General

The manufacturability of an electronic equipment[31,2,32] depends on the techniques used to achieve ease of assembly, component selection, and utilization of design rules consistent with manufacturing processes.

16.9.2 Assembly Considerations

The ease of assembly of an electronic equipment is dependent upon careful design of the product, with produceability and maintainability as major considerations. Products that involve materials requiring few, if any, secondary operations (such as pressing, welding, soldering, drilling, bending, and the need for critical mechanical alignment procedures) are easier to assemble, with fewer quality errors, than products involving many such operations.

Design of components and structures that may be correctly assembled in only one manner, and that may serve more than one function within the product, tend to reduce assembly time and errors. The equipment design must provide adequate physical space for the tools needed to accomplish assembly. Labor-intensive operations such as specifying a joint to be sealed using adhesive may be avoided by specifying an easily installed gasket that may cost less when the cost of the assembly labor plus the cost of the gasket is considered.

16.9.3 Design to Process

The electronic equipment designer must consider the manufacturing processes to be employed in the fabrication of the components and structural elements specified for an equipment. Component part design must be consistent with the available machinery and processes that will be utilized to fabricate the component. This includes the proper selection of materials, component dimensions, edge distances, tooling clearances, process limitations, processing temperatures, application of component finishes, and related issues.

16.9.4 Concurrent Engineering

In the quest for improving product design schedules, equipment quality, and the reduction of project costs, concurrent engineering practices are becoming increasingly common.

Successful concurrent engineering teams work closely together and are required to share product-development information on a nearly real-time basis. This approach permits a variety of team members to work simultaneously on product-design aspects that in the past were handled in a sequential manner. In this way, process engineers, manufacturing engineers, quality control personnel, purchasing personnel, and other team members may influence the design earlier in the product-development process.

16.10 PROTECTIVE PACKAGING

16.10.1 General

Protective packaging includes the techniques employed to ensure that a product will survive handling, shipping, and storage environments without degradation.

16.10.2 Storage Environment Protection

Electronic equipment may be subjected to storage for extended periods of time. The storage environments may include exposure to more severe temperature, pressure, and humidity variations than the product will experience after being placed into service.

Protective packaging selected for storage must withstand the storage environments and offer protection to the enclosed product.

The materials from which storage containers and fillers are selected must be chemically inert and not introduce detrimental effects of the stored equipment. For example, some paper products contain sulfur, the fumes of which accelerate tarnishing, thus increasing contact resistance of silver-plated contacts.

16.10.3 Shipping Environment Protection

Protective packaging must withstand transportation environments and the handling associated with movement of the equipment to, from, and between carriers. The transportation and handling environments may include exposure to more severe shock and vibration than the product will experience after being placed into service.

The shipping containers must tolerate stacking and handling by mechanical lifting devices. When it is predicted that the transportation environment may be more severe than the protected product will withstand, the container may include packing materials to cushion the products from vibration and shock loads. Packaging protection and service life are usually verified by testing prior to use.

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