7

7 Life-Cycle Conditions

The actual loading conditions on a product are often assumed based on engineering specifications or conjecture. This approach can lead to costly overdesign or hazardous underdesign, and consequently, increased investment. Hence, a formal method is necessary to capture the life-cycle load conditions of a product.

This chapter discusses a systematic methodology for developing a life-cycle profile (LCP) for a product. The LCP can thus be used for design and test for reliability assurance. The life-cycle conditions should be collected on actual products if possible.

7.1 Defining the Life-Cycle Profile

The life cycle of a product includes manufacturing and assembly, testing, rework, storage, transportation and handling, operational modes, repair, and maintenance. The life-cycle loads include thermal (steady-state temperature, temperature ranges, temperature cycles, and temperature gradients), mechanical (pressure levels, pressure gradients, vibrations, shock loads, and acoustic levels), chemical (aggressive or inert environments, ozone, pollution humidity levels, contamination, and fuel spills), physical (radiation, electromagnetic interference, and altitude), and/or operational loading conditions (power, power surge, heat dissipation, current, and voltage spikes). The extent and rate of product degradation depend upon the nature, magnitude, and duration of exposure to loads.

Defining and characterizing the life-cycle conditions can be the most difficult part of the overall reliability planning process, because products can be used or not used in different ways, for different amounts of time and with different care, maintenance and servicing. For example, typically all desktop computers are designed for office or home environments. However, the operational profile of each unit will depend on user behavior. Some users may shutdown the computer every time after it is used, others may shut it down only once at the end of the day, while other users may keep their computers powered on all the time. Thus, the temperature profile experienced by each product and hence its degradation due to thermal loads will be different.

Reliability Engineering, First Edition. Kailash C. Kapur and Michael Pecht.

A life-cycle profile (LCP) is a time history of events and conditions associated with a product from its release from manufacturing to its removal from service. The life cycle should include the various phases that the product will encounter in its life. In some cases, the environmental factors experienced by constituents of the product begin before manufacturing—for example, storage of parts (material) in advance of their use in manufacturing.

An LCP helps to identify the possible load combinations so that the loads acting on the product can be identified and their effects can be accounted for in the product's design, test, and qualification process. The reliability of a product depends on the magnitude of the stresses, rate of change of stresses, and spatial variation of the stresses that are generated by the loads acting during its life cycle.

Three key steps are given for the development of LCP:

- The first step is to describe expected events for a product from manufacture through end of life, which involves identifying the different events, which the product will pass through. Typical events include testing and qualification, storage at the test facility, transportation to the place of installation, storage at the place of installation, transportation to the specific site of installation, installation, operation, and field service during scheduled maintenance. It also involves identifying product requirements, such as who will use the product, what platform will carry it, and the operational requirements, deployment, and transportation concepts.
- The second step is to identify significant natural and induced environmental conditions or their combinations for each expected event. This involves identifying the load conditions that act in each of the identified events. The natural environment is the product's natural ambient conditions, for example, temperature, pressure, and humidity. The induced environment is the product's environmental conditions related to the specific functionality of the product. For example, electronics on a drilling tool experience mechanical vibration during the drilling process. Electronics used to control an aircraft engine will include high steady-state temperature dwells, temperature cycling, low pressures, and random vibrations.
- The third step is to describe load conditions to which the product will be subjected during the life cycle, which involves the quantification of load conditions identified as a result of the previous two steps. Data should be determined from real-time measurements but may be estimated by simulation and laboratory tests. For example, the vibrations experienced by a product during shipping could be identified by a mock shipping experiment wherein sensors are kept with the product to record vibration data. The loads should be quantified in a statistical manner to identify the range and variability of the load.

7.2 Life-Cycle Events

Since the LCP is application and product dependent, a thorough analysis of the possible load conditions in each of the events is necessary during the design of any product. Typical loads in most events include temperature, vibration, shock, pressure, humidity, and the induced environments. However, load conditions such as radiation, fungi/microorganisms, fog, freezing rain, snow, hail, sand and dust, salt spray, and wind should not be overlooked. In consumer products, drink spills and food may also be important loads to consider.

7.2.1 Manufacturing and Assembly

Assembly of a product also involves load conditions. For example in assembly of electronic products, soldering operations can lead to significant thermal stresses in the components being assembled, as well as surrounding components. The mechanical handling, placement, and assembly procedures can also induce vibration, shock, and loads. Other load conditions which might be critical are radiation, chemical and ionic contamination (plasma machining or welding), humidity, and pressure, depending on the assembly process.

7.2.2 Testing and Screening

The load conditions a product is subjected to during testing and screening should not affect the product if it is to be subsequently placed in the market. However, tests and screens, such as high-temperature bake, high temperature operating life, vibration, shock, temperature humidity bias (THB), highly accelerated life testing (HALT), and highly accelerated stress testing (HAST), will impact the product reliability and remaining useful life to some extent.

7.2.3 Storage

Storage typically has temperature (diurnal cycles) and humidity as the prime load conditions. However, depending on the quality of the storage facility, load conditions such as rain, snow, fungi, sand and dust, and radiation might also come into the picture. Chemical gases are also an issue when the product is stored in chemically aggressive environments.

7.2.4 Transportation

Transportation is often characterized by high vibration, shock, and temperature loads. Transportation by road can cause shock and vibration due to rocky and uneven paths, internal vibrations, and accidents. The product can also be subjected to diurnal temperature cycles, as well as to heat generated by the operation of the vehicle. Transportation by air can subject the product to vibrations while taking off and landing, as well as to temperature cycling due to the differences in ground and airborne temperatures. Apart from these specific loads, the product can also experience sand and dust, gases, humidity, and radiation.

7.2.5 Installation

The installation process is typically characterized by vibration and shock loads. In deployment of permanent monitoring equipment for oil wells, the equipment suddenly encounters very high temperatures when it comes in contact with the hot oil inside the tubes during deployment.

7.2.6 Operation

The load conditions during operation are specific to the application. For example, an electronic product in the under hood of a car encounters temperature cycling and vibration, whereas the electronics inside a desktop computer has limited vibrations. Humidity, on the other hand, might be a consideration in both of these applications.

7.2.7 Maintenance

Maintenance, in some cases, can subject the product to loads due to handling and mishandling of the product. Shock and vibration are typical loads associated with maintenance procedures. For electronic products, electrostatic discharge can be an issue when proper care is not taken during maintenance.

7.3 Loads and Their Effects

Table 7.1 provides some of the load conditions and their possible effects on products. Some of these conditions are discussed in more detail in the following sections.

7.3.1 Temperature

Temperature can influence the electrical, mechanical, chemical, and physical deterioration of materials for two main reasons: many of the properties of materials can be altered by changes in temperature, and the rate of a chemical reaction between two or more reactants is generally dependent on the temperature of the reactants. Some of the adverse effects of temperature include the expansion or contraction of materials due to temperature changes, causing problems with fit between product interfaces and couplings, outgassing of corrosive volatile products due to application of heat, local stress concentrations due to nonuniform temperature, and the collapse of metal

Table 7.1 Load conditions and their possible effects

Load conditions		Principal effects	Possible Failures
Temperature (natural/induced)	High	■ Thermal aging ■ Oxidation ■ Structural change ■ Chemical change ■ Softening and melting ■ Viscosity reduction/ evaporation ■ Physical expansion	■ Insulation failure because of melting ■ Alteration of electrical properties due to changes in resistance ■ Unequal expansion between coupled parts leading to fatigue or fracture ■ Ionic contamination ■ Surface degradation
	Low	■ Physical contraction ■ Brittleness	■ Alteration of electrical properties due to changes in resistance ■ Unequal expansion between coupled parts, leading to fatigue or fracture ■ Increased brittleness of metals

Table 7.1 (*Continued*)

Load conditions		Principal effects	Possible Failures
Relative humidity/ moisture (natural/induced)	High	■ Moisture absorption ■ Chemical reaction ■ Corrosion ■ Electrolysis	■ Corrosion ■ Electrical shorting ■ Loss of electrical properties owing to corrosion and chemical reactions ■ Cracking of materials due to moisture absorption ■ Reduction in electrical resistance because of conduction through moisture
	Low	■ Desiccation ■ Embrittlement ■ Granulation	■ Loss of mechanical strength ■ Structural collapse ■ Alteration of electrical properties
Pressure (natural/induced)	High	■ Compression	■ Structural collapse ■ Penetration of seals ■ Interference with function
	Low	■ Expansion ■ Outgassing	■ Explosive expansion of parts ■ Alteration of electrical properties ■ Loss of mechanical strength ■ Insulation breakdown
Wind (natural)		■ Force application ■ Deposition of materials ■ Heat loss (low velocity) ■ Heat gain (high velocity)	■ Structural collapse ■ Interference with function ■ Loss of mechanical strength ■ Mechanical interference and clogging ■ Accelerated abrasion ■ Removal of protective coatings ■ Surface deterioration
Salt spray (natural)		■ Chemical reactions ■ Corrosion ■ Electrolysis	■ Increased wear ■ Alteration of electrical properties ■ Interference with function ■ Surface deterioration ■ Increased conductivity
Sand and dust (natural)		■ Abrasion ■ Clogging	■ Increased wear ■ Interference with function ■ Alteration of electrical properties ■ Removal of protective coatings ■ Surface deterioration
Rain (natural)		■ Physical stress ■ Water absorption and immersion ■ Erosion ■ Corrosion	■ Structural collapse ■ Increase in weight ■ Electrical failure ■ Structural weakening ■ Removal of protective coatings ■ Surface deterioration ■ Enhanced chemical reactions like corrosion
Ionized gases (natural)		■ Chemical reactions ■ Corrosion ■ Change in conductivity	■ Change in electrical properties ■ Deterioration in material properties

(*Continued*)

Table 7.1 (*Continued*)

Load conditions	Principal effects		Possible Failures
Air pollution (natural)	■ Chemical reactions ■ Clogging		■ Interference in functionality ■ Deterioration in material properties owing to chemical reactions ■ Corrosion
Freezing rain/ frost/snow (natural)	■ Low temperature ■ Moisture ingress ■ Corrosion/chemical reactions ■ Clogging		■ Mechanical stress caused by expansion mismatch between structural components ■ Increase in weight ■ Change in electrical properties due to change in resistance/conductivity ■ Delamination of materials ■ Material deterioration ■ Corrosion
Fungi (natural)	■ Clogging		■ Change in electrical characteristics due to shorts and alteration in electrical resistance ■ Oxidation of structural elements
■ Static electricity ■ Electrostatic discharge (natural/induced)	■ Change in electrical response ■ Electrical overstress		■ Interference in function due to changes in electrical properties (resistance, voltage) ■ Shorts or opens in circuit
Chemicals (induced)	■ Chemical reactions ■ Reduced dielectric strength		■ Alteration of physical and electrical properties ■ Insulation breakdown ■ Corrosion
Explosion (induced)	■ Severe mechanical stress		■ Rupture and cracking ■ Structural collapse of the product
Shock (induced)	Thermal	■ Mechanical stress	■ Unequal expansion between coupled materials of the product leading to fatigue or fracture ■ Surface degradation ■ Melting
	Mechanical	■ Mechanical stress ■ Fatigue	■ Loss of mechanical strength ■ Interference with function ■ Increased wear ■ Fatigue ■ Structural collapse of products
Vibration (induced)	■ Vibration/ acceleration	■ Mechanical stress ■ Fatigue	■ Loss of mechanical strength ■ Interference with function ■ Increased wear ■ Fatigue ■ Structural collapse of product
	■ Rotation	■ Mechanical stress ■ Torsional acceleration	■ Twisting of parts ■ Loss of mechanical strength ■ Deformation
	■ Bending	■ Mechanical stress ■ Fatigue	■ Bending failure ■ Cracking ■ Deformation

structures when subjected to cyclic heating and cooling due to induced stresses and fatigue caused by repeated flexing.

7.3.2 Humidity

Water vapor in the air or any other gas is called "humidity"; water in solids or absorbed in liquids is usually designated "moisture." Relative humidity (RH) is the ratio of actual vapor pressure to saturation vapor pressure at the prevailing temperature. It is usually expressed as a percentage. Absolute humidity is the mass of water vapor per unit mass of dry air in the sample volume at the prevailing temperature. Vapor pressure is the part of the total pressure contributed by the water vapor. Dew point temperature is the temperature to which a gas must be cooled at constant pressure to achieve saturation.

Humidity or moisture can play a major role in accelerating failures in products. Failure mechanisms, such as corrosion, contamination, and swelling of polymer-based structural elements or potting, are all adversely impacted by the presence of moisture. Moisture can cause mated parts in a product to lock together, especially when water condenses on them and then freezes. Many materials that are normally pliable at low temperatures can become hard and brittle due to absorption of water, which subsequently freezes at low temperatures. The volume increase due to freezing of water can also separate parts, materials, or connections.

Moisture can also act as a medium for the interaction between several otherwise relatively inert materials. For example, chlorine will be released by polyvinyl chloride (PVC), and form hydrochloric acid when combined with moisture. Moisture with certain ionic materials can cause shorts or leak paths between metal traces or adjacent conductors on printed circuit boards in electronic products.

Although the presence of moisture may cause deterioration, the absence of moisture can also cause reliability problems. Many nonmetallic materials become brittle and crack when they are very dry. The properties of these materials depend upon an optimum level of moisture. For example, fabrics wear out at an increasing rate as moisture levels are lowered, and fibers become dry and brittle. Environmental dust, which is usually held in suspension by moisture, can cause increased wear and friction on moving parts. Freed dust can clog filters due to the absence of moisture.

Design techniques can be used to counteract the effects of moisture. For example, moisture traps can be eliminated by providing drainage or air circulation, using desiccant systems to remove moisture when air circulation or drainage is not possible, applying protective coatings, providing rounded edges to allow uniform coating of protective material. Using materials resistant to fungi, corrosion, and other moisture-related effects and hermetically sealing components by using gaskets and other sealing products can also prevent degradation due to moisture. Other design techniques include impregnating or encapsulating materials in moisture-resistant waxes, plastics, or varnishes, separating dissimilar metals or materials that might combine or react in the presence of moisture or of components, which might damage protective coatings.

The design team must consider possible adverse effects caused by specific methods of protection. Hermetic sealing, gaskets, and protective coatings may, for example, increase moisture by sealing moisture inside or contributing to condensation. Gasket materials must be evaluated carefully for outgassing of volatile vapors or for incompatibility with adjoining surfaces or protective coatings.

7.3.3 Vibration and Shock

Vibrations result from dynamic forces that set up a series of motions within a product. The forced motions may be linear, angular (torsion), or a combination of both. A vibratory system includes, in general, a means for storing potential energy (spring or elasticity), a means for storing kinetic energy (mass or inertia), and a means by which energy is gradually lost (damping or resistance).

Fatigue, which is the tendency of a material to yield and fracture under cyclic stress loads considerably below its tensile strength, is a failure mechanism that may result from vibrations. Fatigue failures include high cycle fatigue, acoustic fatigue, and fatigue under combined stresses such as temperature extremes, temperature fluctuations, and corrosion.

Some of the common faults that may be caused by vibration include bent shafts, damaged or misaligned drives and bearings, fretting corrosion, onset of cavitations, and worn gears. Vibration and shock can harmfully flex electrical leads and interconnects, cause parts to strike the housing, dislodge parts from their positions, cause acoustical and electrical noise, and lead to structural instabilities.

Protective measures against vibration and shock are generally determined by an analysis of the deflections and mechanical stresses produced by these load conditions. This involves the determination of natural frequencies and evaluation of the mechanical stresses within components and materials produced by the shock and vibration environment. If the mechanical stresses are below the acceptable safe working stress levels of the materials involved, no direct protection methods are required. If the stresses exceed the safe levels, corrective measures such as stiffening, reduction of inertia and bending moment effects, and incorporation of further support members, as well as possible uses of isolators, may be required. If such approaches do not reduce the stresses below the acceptable safe levels, further reduction is usually possible by the use of shock-absorbing mounts.

In addition to using proper materials and configurations, it is necessary to control the amount of shock and vibration experienced by the product. Damping systems are used to reduce peak oscillations and special stabilizers can be employed when unstable configurations are involved. Typical examples of dampers are viscous hysteresis, friction, and air damping. Vibration isolators are commonly identified by their construction and material used for resilient elements like rubber, coiled spring, and woven metal mesh. Shock isolators differ from vibration isolators in that shock requires a stiffer spring and a higher natural frequency for the resilient element. Isolation mounting systems are of the type installed underneath, the over-and-under type, and inclined isolators. In some cases, however, even though a product is properly insulated and isolated against shock and vibration damage, repetitive forces may loosen the fastening systems. If the fastening systems loosen enough to permit movement, the product will be subjected to increased forces and may fail. Many specialized self-locking fasteners are available to counter this occurrence.

7.3.4 Solar Radiation

Solar radiation contributes several types of loads to the life-cycle environment. The solar flux provides radiant heating, ionizing radiation, including ultraviolet exposure, and visible wavelengths that can interfere with optics.

The maximum solar load outside the atmosphere occurs on January 2 of each year when the Earth is closest to the sun. The solar flux is taken at an average of 1367 W/m^2, with a January peak of 1413 W/m^2 and the July 4 minimum at 1332 W/m^2. The sun can be modeled as a black body radiator at 6000 K. Therefore, the sun emits ultraviolet (UV) radiation. Objects in orbit receive this flux projected onto their area unless shadowed by the Earth. The Earth's atmosphere attenuates and scatters much of the incident solar energy. The solar radiation on objects on the surface of the Earth is the sum of the projected area normal to the Earth–sun line flux, a function of the time of day and location, energy incident by a scattered path, and energy reflected off other surface objects.

The primary effect of sunlight is heating. Surface temperatures in space are directly dependent upon the ratio of solar absorbtivity to infrared emissivity. This ratio is important on the surface of the Earth, but convection also plays a dominant role in determining surface temperatures.

The sun's light also provides damaging UV radiation on products. For example, organics used in plastics and paints, wiring, cables, and connectors are especially vulnerable to damage by UV radiation. Optical components such as security cameras are vulnerable to damage by heat, direct solar exposure, thermal loading, and functional interference by glint or overexposure.

7.3.5 Electromagnetic Radiation

Products stored near nuclear reactors, isotropic nuclear sources, accelerators, or nuclear detonations must be designed to tolerate the effects of nuclear irradiation. For example, time-dependent wearout failures can cause an embrittlement phenomenon that increases the hardness and decreases the ductility of metals. Another failure mechanism is random overstress when a single radiation particle interacts with the electronic circuitry.

In general, metals are quite resistant to radiation damage in the space environment. Semiconductor devices may be affected by gamma rays, which increase leakage currents. The lattice structure of semiconductors can be damaged by high energy electrons, protons, and fast neutrons, which cause permanent effects through atomic displacement and damage to the lattice structure. Organic materials are particularly susceptible to physical changes in cross-linking and scission of molecular bonds. Radiation-induced formation of gas, decreased elasticity, and changes in hardness and elongation are some of the predominant changes in plastics which have been subjected to radiation of the type encountered in the space environment.

Protection against the effects of electromagnetic radiation has become an engineering field by itself: electromagnetic compatibility design. The most direct approach to protection is to entirely avoid the region in which high radiation levels are found. When exposure cannot be avoided, shielding and filtering are the protective measures used. In other cases, material design changes or operating procedural changes must be instituted in order to provide protection or to minimize the effects on normal operation of the product.

7.3.6 Pressure

Pressure is defined as the normal force per unit area exerted by a fluid (either a liquid or a gas) on any surface. The surface is typically a solid boundary in contact with the fluid. Finding the component of the force normal to the surface is sufficient for determining the pressure. Pressure can be expressed in four ways:

- *Absolute Pressure.* The same as the definition given above. It represents the pressure difference between the point of measurement and a perfect vacuum where the pressure is zero.
- *Gage Pressure.* The pressure difference between the point of measurement and the ambient pressure.
- *Differential Pressure.* The pressure difference between two points, one of which is chosen to be the reference.
- *Stagnation Pressure.* The pressure due to fluid flow.

In high vacuum conditions (such as space), materials having a high vapor pressure will sublimate or evaporate rapidly, particularly at elevated temperatures. In some plastics, the loss of the plasticizing agent by evaporation will cause cracking, shrinking, or increased brittleness. Inorganic coatings with low vapor pressures can be used to protect metals such as magnesium, which would normally evaporate rapidly.

In a high vacuum, adjoining solid surfaces can become cold-welded after losing adsorbed gases from their surfaces. Some form of lubrication is therefore necessary. Conventional oils and greases evaporate quickly. Graphite becomes unsatisfactory and actually behaves as an abrasive because of the loss of absorbed water. However, thin films of soft metals, such as lead, silver, or gold, are effective lubricants in a high vacuum. Thin films of molybdenum disulfide are often sprayed over chrome or nickel plating, forming easily sheared layers.

7.3.7 Chemicals

The Earth's environment contains numerous chemically active elements, such as sulfur, phosphorus, chlorine, nitrogen, snow, ice, sand, dust, saltwater spray, and organic matter, which have the ability to corrode and deteriorate materials.

A material or structure can undergo a chemical change in a number of ways. Among these are interactions with other materials, such as corrosion, metal migration and diffusion, and modifications in the material itself, such as recrystallization, stress relaxation, and phase change. In addition to the deterioration problems associated with the external environments to which products are subjected, adhesives, batteries, and certain types of capacitors are susceptible to chemical aging and biological growths due to biochemical reactions.

Materials widely separated in the electrochemical series are subject to galvanic action, which occurs when two chemically dissimilar metals are in contact in an electrolytic liquid medium. The more active metal dissolves, and an electric current flows from one metal to the other. Coatings of zinc are often applied to iron so that the zinc, which is more active, will dissolve and protect the iron. This process is commonly known as "galvanization." Galvanic action is also known to occur within the same piece of metal if one portion of the metal is under stress and has a higher free-energy level than the other. The part under stress will dissolve if a suitable liquid medium is present.

Stress-corrosion cracking occurs in certain magnesium alloys, stainless steels, brass, and aluminum alloys. It has also been found that a given metal will corrode much more rapidly under conditions of repeated stress than when no stress is applied.

Proper design of a product therefore requires trade-offs in selecting corrosion-resistant materials, specifying protective coatings, use of dissimilar metallic contacts, controlling metallurgical factors to prevent undue internal life-cycle conditions, preventing water entrapment, using high temperature resistance coatings when necessary, regulating the environment through dehydration, rust inhibition, and electrolytic and galvanic protective techniques.

7.3.8 Sand and Dust

In relatively dry environments, such as deserts, fine particles of dust and sand can readily be agitated into suspension in the air, where they may persist for many hours, sometimes reaching heights of several thousand feet. Thus, even though there is virtually no wind present, the speed of vehicles that may be housing an electronic product and moving through these dust clouds can also cause surface abrasion by impact.

Although dust commonly is considered to be fine, dry particles of earth, it also may include minute particles of metals, combustion products, and solid chemical contaminants. These other forms may cause direct corrosion or fungal effects on products, because this dust may be alkaline, acidic, or microbiological. Dust accumulations have an affinity for moisture, and this may accelerate corrosion and biological growth.

Dust reduction methods are mainly of two types: active and passive. Active methods include installation of fans to increase the flow of air and use of filters and shelters. Passive methods include measures such as planting trees, and improving pollution standards. Dust protection must be planned in conjunction with protective measures against other environmental factors. For example, specifying a protective coating against moisture, if sand and dust are present, is useless unless the coating is carefully chosen to resist abrasion and erosion. When products require air circulation for cooling or for removing moisture, the issue is not whether to allow dust to enter, but rather to control the size of the dust particles. The problem becomes one of filtering the air to remove dust particles above a specific nominal size. For a given working filter area, these filters decrease the flow of air or other cooling fluids through the filter, while the ability of the filter to stop smaller and smaller dust particles is increased. Therefore, there must be a trade-off between the filter surface and the decrease of flow of the fluid through the filter or the allowable particle size.

7.3.9 Voltage

Voltage load in the form of input voltage, feedback voltage, voltage drops, and transient spikes can affect functionality and trigger several failure mechanisms in electronic products. Over voltage can cause electrical overstress (EOS). High voltages may also result in gate oxide breakdown. The high voltage (100 V to 20 KV) associated with electrostatic discharge (ESD) can cause damage to thin dielectrics, such as the gate oxides in CMOS processes, and the high energy can result in thermal damage in both bipolar and CMOS devices. Low voltage electrostatic pulse can cause damage to the gate oxides of MOS transistors if no protection circuit is present. Drain-source shorts are the most severe form of damage observed.

7.3.10 Current

Current loads manifests as steady-state high level of current, current variations, excessive leakage current (such as supply leakage, gate leakage, and drain-source leakage), and transient current spikes. This load condition is particularly important for electronic products. Supply current monitoring is routinely performed for testing of CMOS ICs. This method is based upon the notion that defective circuits produce an abnormal or at least significantly different amount of current than the current produced by fault-free circuits. This excess current can be sensed to detect faults. The high power supply quiescent current has been reported as a precursor for defects such as bridging, opens, and parasitic transistor defects.

Overcurrent can cause electrical overstress (EOS). As the semiconductor junctions get hotter, more current flows in the hot regions and a thermal runaway condition is reached. Eventually, the device is driven into a second breakdown as the temperature approaches the melting point of silicon. Failures may be due to silicon melting, causing the junctions to short circuit, or the metallization to melt and open circuit.

7.3.11 Human Factors

Humans can directly induce load conditions to a product. Humans are active participants in the operation of most systems, and this interaction must be weighed against safety, reliability, maintainability, and other product parameters to assess product reliability, maintainability, time performance, safety analyses, and specific human engineering design criteria. Humans by virtue of the way they handle a product can contribute to failures and affect the reliable operation of the product.

7.4 Considerations and Recommendations for LCP Development

The following are recommendations for obtaining data on the load conditions.

7.4.1 Extreme Specifications-Based Design (Global and Local Environments)

Extreme environmental conditions in the location of deployment of the product are often used for design.[1] Extreme conditions are unlikely to be encountered by the product in its lifetime. Moreover, the duration of maximum conditions is typically short. Further, the environment in the vicinity of the product can be modified by its functionality (local environment). Hence, the use of extreme-based specifications for the design of a product can lead to overdesign or underdesign (due to a change in the local environment).

The part's local environment, that is, the environment in the immediate vicinity of the part, often varies from the overall product's global environment, that is, the environment in the larger vicinity of the part For example, the local environment of certain parts in a desktop computer, given the heat generated from the power dissipation of the parts on the board, will be significantly hotter than the regulated office

[1]The highest temperature recorded on Earth is 57.77°C in Al Aziziyah, Libya, in September 1922. Death Valley, California, recorded 56.77°C in July 1913. The place that has the world's highest average temperature is Dakol, Ethiopia, in the Danakil Depression, with a mean temperature of 34.44°C. Places in Pakistan (e.g., Pad Idan) have recorded temperatures up to 50.55°C. The lowest recorded temperature on Earth to date is −89.44°C in Vostok, Antarctica.

environment.[2] The variation between the global environment and the local environment may be a function of the part's isolation from the global environment, the existence of cooling systems within the product, the heat generated by nearby parts, and insulating air between the part and the product environment.

For example, the lowest recorded ambient temperature in Greenland is –70°C. To meet needed performance and reliability objectives, the local environment of parts in products located in Greenland must be thermally insulated or regulated (i.e., through the use of heaters). The design procedure should incorporate extreme specifications as a baseline, along with their probability of occurrence, and should modify it according to the expected local environments.

7.4.2 Standards-Based Profiles

Standards-based environmental data can be found in standards including MIL-STD-210 (United States Department of Defense 1987), MIL-STD-810 (United States Department of Defense 1989), and IPC-SM-785 (1992). MIL-STD-210 is a database of regional and worldwide climatic data. The data are divided into three groups—worldwide surface environment, regional surface environment, and worldwide air environment—and include details about basic regional types: hot regions, cold regions, severe cold regions, and coastal/ocean regions. The load conditions discussed for each of the groups include temperature, humidity, pressure rainfall rate, wind speed, blowing snow, snow load, ice accretion, hail size, ozone concentration, sand and dust, and freeze-thaw cycles in terms of extreme values, nominal (average) values, and frequency of occurrences. In spite of the details provided in MIL-STD-210, climatic data derived from this standard should not be used directly for design criteria. Rather, they should be used to derive design criteria for each product based on the response of the product to both the natural environment and the forcing functions induced by the platform on or within which the product is located (local environments).

MIL-STD-810 provides guidelines for conducting environmental engineering tasks to tailor environmental tests to end-item product applications. It contains test methods for determining the effects of natural and induced environments on product performance and is mainly focused on system-level design. The conditions and procedures described in MIL-STD-810 can be used for deriving the LCP for electronic products. Other standards, like those of the EIA, IPC, and SAE, also provide environmental data, which can be used to derive the LCP.

7.4.3 Combined Load Conditions

Combined loads (incorporating two or more environmental factors) may affect product reliability differently than a single environmental factor. If the combined effect of the environmental factors proves to be more harmful than that of a single environmental condition, then the product must be designed for failures arising from the combined effects. Some examples of the possible effects of pairs of environmental factors appear in Table 7.2.

An increase in one environmental factor can lead to an increase in another, thereby intensifying the net effect. For example, high temperatures accelerate the growth of

[2]For example, the local environment of certain parts in a desktop computer, given the heat generated from the power dissipation of the parts on the board, will be significantly hotter than the regulated office environment.

Table 7.2 Examples of generic effects of combined loads on products

Combined loads	Classification of effects	Possible effects
High temperature and salt spray	Intensified deterioration	High temperature tends to increase the rate of corrosion caused by salt spray and thereby increase the net effect.
High temperature and high relative humidity	Intensified deterioration	High temperature increases the rate of moisture penetration and the rate of corrosion. Thus the combination can aggravate failures caused by humidity (e.g., corrosion).
High temperature and high pressure	Intensified deterioration	Each of these environmental factors leads to deterioration in the strength of the material and can cause structural failure in electronic assemblies.
High temperature and fungi	Intensified deterioration	High temperatures provide a congenial environment for growth of fungi and microorganisms. Thus high temperatures aggravate failures caused by fungal growth.
High temperature and acceleration	Intensified deterioration/ weakened net effect	Both acceleration and high temperature affect material properties. The combination, however, can reduce failure caused by fatigue/ fracture because the material stress relaxes at high temperatures and the material becomes more pliable. In the case of brittle materials, however, this combination can lead to early failures because the material becomes weak at high temperatures and can easily fracture. In electronic products, failures caused by solder joint fatigue and cracking are diminished by the combination.
High temperature, sand, and dust	Intensified deterioration/ weakened net effect	The erosion caused by sand may be accelerated by high temperature, which can cause wear of structural parts due to abrasion. High temperature also reduces the penetration of sand and dust, thereby decreasing failures that occur from dust penetration.
High temperature, shock, and vibration	Intensified deterioration/ weakened net effect	Vibration, shock, and high temperature affect material properties and cause deterioration of mechanical properties. The combination, however, reduces failure caused by fatigue/fracture, because the material stress relaxes at high temperatures and the material becomes more pliable. Failures caused by solder joint fatigue and cracking are diminished by the combination. In case of brittle materials, however, this combination can lead to early failures because the material becomes weak at high temperatures and can easily fracture.
Low temperature and humidity	Intensified deterioration	Relative humidity increases as temperature decreases (especially in moist conditions), and lower temperature may induce moisture condensation. If the temperature is low enough, frost or ice may result. Hence, low temperatures can aggravate failures caused by humidity, frost, or ice (e.g., corrosion).
Low temperature and high pressure	Intensified deterioration	The combination can cause structural failure, such as leakage through seals and airtight enclosures.
Low temperature and salt spray	Weakened net effect	Low temperature reduces the corrosion caused by salt spray; the combination causes weakening.
Low temperature, sand, and dust	Intensified deterioration	Low temperature increases dust penetration and can aggravate failures caused by wear of assemblies and alteration of electrical properties.

Table 7.2 (*Continued*)

Combined loads	Classification of effects	Possible effects
Low temperature and fungi	Weakened effect	Low temperature reduces fungus growth. At subzero temperatures, fungi remain in suspended action, thereby weakening the net effect.
Low temperature, shock, and vibration	Intensified deterioration	Low temperature tends to intensify the effects of shock and vibration, because certain materials (such as aluminum) tend to become brittle at lower temperatures. However, this is a consideration only at very low temperatures.
Low temperature and acceleration	Intensified deterioration	Acceleration produces shock, vibration, or both. Hence, low temperature and acceleration intensify the effects of acceleration because of brittleness at low temperatures.
Humidity and high pressure	Intensified deterioration	The effect of this combination varies with the temperature. High temperature can aggravate the deleterious effects caused by humidity and high pressure, indirectly increasing the net effect on a product.
Humidity and salt spray	Intensified deterioration	High humidity may dilute the salt concentration and could affect the corrosive action of the salt by increasing its mobility and spread, thereby increasing the conductivity. Corrosion failures are typically aggravated.
Humidity and fungi	Intensified deterioration	Humidity helps the growth of fungus and microorganisms but adds nothing to their effects.
Humidity, sand and dust	Intensified deterioration	Sand and dust have a natural affinity for water, and this combination increases deterioration by corrosion.
Humidity and vibration	Intensified deterioration	This combination tends to increase the rate of breakdown of material and connections.
Humidity, shock, and acceleration	Intensified deterioration	The periods of shock and acceleration, if prolonged, aggravate the effects of humidity, because humidity tends to cause deterioration of material properties. The combination can lead to early structural failure.
High pressure and vibration	Intensified deterioration	This combination intensifies structural failures in a product.
High pressure, shock, and acceleration	Intensified deterioration	This combination intensifies structural failures in a product.
Salt spray and dust	Intensified deterioration	Sand and dust have a natural affinity for water, and this combination increases deterioration by corrosion.
Salt spray, shock, or acceleration	Coexistence without any synergistic effects on deterioration of the product	These combinations produce no added effect.
Salt spray and vibration	Intensified deterioration	This combination tends to increase the rate of breakdown of material and connections.
Salt spray and explosive atmosphere	Incompatible	This is considered an incompatible combination.
Sand, dust, and vibration	Intensified deterioration	Vibration increases the wearing effects of sand and dust.

(*Continued*)

Table 7.2 (*Continued*)

Combined loads	Classification of effects	Possible effects
Shock and vibration	Coexistence without any synergistic effects on deterioration of the product	Since shock is a form of vibration, this combination does not produce any added effects.
Vibration and acceleration	Intensified deterioration	This combination produces increased effects when encountered with high temperatures and low pressures (typically in applications such as oil suction).
High temperature and low pressure	Intensified deterioration	As pressure decreases, outgassing of constituents of materials increases. As temperature increases, outgassing increases. Hence, each tends to intensify the effects of the other.
High temperature and explosive atmosphere	Coexistence without any synergistic effects on deterioration of the product	Temperature has minimal effect on the ignition of an explosive atmosphere but does affect the air–vapor ratio, which is an important consideration.
High pressure and explosive atmosphere	Intensified deterioration	High pressure aggravates the effects of explosion and thereby enhances the hazards of an explosive atmosphere.
Low temperature and low pressure	Intensified deterioration	This combination can accelerate leakage through seals and airtight regions. It can cause material deterioration and loss of functionality in hermetic parts.
Low temperature and explosive atmosphere	Coexistence without any synergistic effects on deterioration of the product	Temperature has minimal effect on the ignition of an explosive atmosphere but does affect the air–vapor ratio, which is an important consideration.
Humidity and explosive atmosphere	Weakened net effect	Humidity has no effect on the ignition of an explosive atmosphere, but high humidity will reduce the pressure of an explosion.
Low pressure and salt spray	Intensified deterioration	This combination can lead to increased penetration of moisture into the product and thus enhance the rate of material deterioration and corrosion-related failure mechanisms.
Low pressure and fungi	Coexistence without any synergistic effects on deterioration of the product	This combination does not add to overall effects.
Low pressure and explosive atmosphere	Intensified deterioration	At low pressures, an electrical discharge is easier to develop, but the explosive atmosphere is harder to ignite.

some fungi and microorganisms. With a small amount of humidity present, microorganisms can grow on electronic assemblies and the organic processes can cause chemical changes and contamination, resulting in loss of performance.

In some cases, two load conditions may act independently on a product and do not influence each other's effect. For example, acoustic vibrations to which electronic product might be subjected do not have any significant additive effect on the potential hazards caused by fungal activity in the vicinity of electronic parts.

In some cases, two load conditions may diminish the effect of each other. For example, high temperature can increase outgassing of constituents of the structural material of electronic parts, while high pressure generally decreases it. Permanently installed downhole gauges typically experience high temperature and high pressure conditions.

The increase in one load condition can also lead to the reduction of another; consequently, the net effect is reduced. For example, low temperature generally retards growth of fungi; therefore, the effects of the presence of fungi are reduced with low temperature.

7.4.4 Change in Magnitude and Rate of Change of Magnitude

Failure mechanisms in a product can be caused by steady-state loads or changes in the magnitude of the load (absolute change or rate of change). Therefore, the nature of the application of the loads (steady state or dynamic) should be determined. For example, in electronic products, functional failures caused by reduced propagation of signals is often caused by high temperature conditions, while failures in electrical interconnections often depend more on the rate of temperature change (Lall et al. 1997).

7.5 Methods for Estimating Life-Cycle Loads

The life-cycle loads need to be quantified in terms of range of possible values and expected variability of these values. Ideally, the design team should know the distribution of the loads experienced by the product. Several methods to quantify the life-cycle loads are discussed in the next section. Methods such as conducting in situ monitoring provide the most accurate information. Designs that are based on life-cycle loads obtained from market studies and field trials are usually much less accurate.

7.5.1 Market Studies and Standards Based Profiles as Sources of Data

Market surveys and reports generated independently by agencies[3] or conducted by industries as a part of their design process are often used as the basis for load conditions characterization. These kinds of data are derived most often from a similar kind of load conditions and give a very coarse estimate of the actual load conditions that

[3] These agencies include focus groups in organizations and standards committees like those that develop military standards. For example, IPC SM-785 specifies the use and extreme temperature conditions for electronic products categorized under different industry sectors, such as telecommunication, commercial, and military.

the targeted product will experience. The use of standard-based profiles such as military standards and IPC was discussed in the previous section. These methods should only be applied after similarity analysis shows considerable agreement with the new product.

7.5.2 In Situ Monitoring of Load Conditions

Environmental and usage loads experienced by the product in its life cycle can be monitored in-situ. These data are often collected using sensors, either mounted externally or integrated with the product and supported by telemetry systems. Devices such as health and usage monitoring systems (HUMS) are popular in aircraft and helicopters for in situ monitoring of usage and environmental loads.

Load distributions should be developed from data obtained by monitoring products used by different customers, ideally from various geographical locations where the product is used. The data should be collected over a sufficient period to provide an accurate estimate of the loads and their variation over time. In situ monitoring has the potential to provide the most accurate account of load history for use in design and test of future products.

7.5.3 Field Trial Records, Service Records, and Failure Records

Field trial records are sometimes used to get estimates on the load profiles. Field trial records provide estimates on the load conditions experienced by the product. The data depend on the durations and conditions of the trials, and can be extrapolated to get an estimate of actual load conditions.

Service records and failure records usually document the causes for scheduled or unscheduled maintenance and the nature of failure in the product, which might have been due to certain load or usage conditions. These data are sometimes used to estimate the kinds of load conditions the product might be subjected to.

7.5.4 Data on Load Histories of Similar Parts, Assemblies, or Products

Similarity analysis is a technique for estimating loads when sufficient field histories for similar products are available. Before using data on existing products for proposed designs, the characteristic differences in design and application for the two products need to be reviewed. Changes and discrepancies in the conditions of the two products should be critically analyzed to ensure the applicability of available loading data for the new product. For example, electronics inside a washing machine in a commercial laundry is expected to experience a wider distribution of loads and use conditions (due to several users) and higher usage rates compared with a home washing machine. These differences should be considered during similarity analysis.

7.6 Summary

To design a reliable product, it is necessary to understand the events and loads that a product will experience throughout its life cycle. Many times, the life-cycle events and loads of a product are merely assumed based on engineering specifications or conjecture. But this approach can lead to costly overdesign or hazardous underdesign, resulting in increased investment and risk. Hence, a formal method is needed to capture the life-cycle events and loads that a product will experience. Such a method involves determining systematically the life-cycle profile of a product based on data collected from actual products, if at all possible.

A life-cycle profile is a time history of events and conditions associated with a product from its release from manufacturing to its removal from service. There are three steps in the development of a life-cycle profile. The first step is to describe expected events for a product from manufacture through end of life, which involves identifying the different events that the product will pass through. The second step is to identify significant natural and induced environmental conditions or their combinations for each expected event. The third step is to describe load conditions to which product will be subjected during the life cycle, which involves the quantification of load conditions identified as a result of the previous two steps. Beyond these three steps, there are certain considerations that companies should take into account when developing life-cycle profiles for their products. These considerations include life-cycle profile recommendations from standards, the impact of combined loads on their products, and changes in the magnitude of loads.

Recommended methods for estimating life-cycle loads include conducting market studies and researching standards-based profiles to collect data. Various sensors and prognostic and diagnostic techniques can be used for in situ monitoring of load conditions in a product. Data can also be culled from field trial records, service records, and failure records, as well as from load histories from similar parts, assemblies, or products. As these data are collected and analyzed, companies will be able to predict with increasing accuracy the life-cycle events that their products will experience, thus enabling them to produce products in a way that minimizes cost and maximizes reliability.

Problems

7.1 Poor manufacturing, handling, assembly, storage, and transportation are often found as early failure causes. Can the life-cycle profile for a product help in reduction of early failures? Explain using the example of incandescent (tungsten filament) light bulbs.

7.2 Prepare a life-cycle profile for a bicycle for three different usage conditions: commuting from apartment or dormitory to school, courier service in a city and recreational mountain biking.

7.3 Prepare a life-cycle profile for a military heavy-lift helicopter. What the operational and environmental conditions that the helicopter will be subjected too?

7.4 What are the different combined loads that a car can experience? How can these combined loads affect the reliability of the car? What are the failure mechanisms that are induced by the combined loads?