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ELECTRONICS INDUSTRIES

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Guidelines for Accelerated Reliability Testing of Surface Mount Solder Attachments

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A guideline developed by IPC

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Developed by the SMT Accelerated Reliability Test Task Group of the
Product Reliability Committee of IPC

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Guidelines for Accelerated Reliability Testing of Surface Mount Solder Attachments

1.0 SCOPE

This document provides guidelines for accelerated reliability testing of surface mount solder attachments and for evaluating and extrapolating the results of these accelerated reliability tests towards actual use environments of electronic assemblies. Background and design information is provided for an understanding of the accelerated test issues.

1.1 Purpose The purpose of accelerated reliability testing is to provide confidence that the design and the manufacturing/assembly processes are capable of meeting the intended goals of product performance. These guidelines provide adequate commonality and validity for accelerated reliability tests:

- To allow comparison of results from different test programs
- To provide the generic technical understanding of the underlying issues necessary to the design for adequate reliability
- To permit the analytical prediction of reliability based on a generic database and technical understanding
- To reduce cost and avoid time-consuming testing of every design iteration
- To establish practical alternatives to replace the excessively long test durations necessary to verify reliability of products subject to severe use environments or low failure tolerances

1.2 Document Organization This document has been organized to provide the reader with consistent information on the various aspects of reliability and identifies the parameters that need to be addressed. Each section serves a specific function in the reliability description chain. Where appropriate, references are provided as to where additional information may be obtained.

• Section 3, “Requirements”

This section provides an overview of the concepts of reliability and all of the characteristics that need to be considered in the validation of a product design. Included are the definitions of the appropriate terms, as well as generic models for fatigue life and failure probability, manufacturing process flow, use environments, and testing methodology.

• Section 4, “Surface Mount Solder Attachment Fatigue Behavior and Prediction”

This section deals with the fatigue life models for solder joints including their behavior when subjected to multiple

cyclic loads during large temperature excursions or high frequency cycles at low temperatures. Also discussed are the acceleration factors, the acceleration transforms, and statistical considerations.

• Section 5, “Design for Solder Joint Reliability”

This section details the various design parameters that have a primary influence on solder attachment fatigue reliability. All aspects of the solder joint formation are addressed including component size, lead stiffness, coefficient of thermal expansion, solder joint uniformity, as well as solder composition, grain structure and the value that conformal coating or compliant layers provide to the attachment system.

• Section 6, “Manufacturing Processes”

This section provides the relationship between the assembly and attachment processes, including their control and verification, and the resultant defects or potential defects from the original processes or touch-up, rework or repair actions. Material properties of solder (including volume), components, printed boards, adhesives and conformal coatings are discussed as to their interrelationships and the impact that these characteristics have on the manufacturing processes.

• Section 7, “Accelerated Reliability Testing”

This section deals with the goals of accelerated testing to produce a failure in the shortest time using techniques intended to simulate the use environment in order to establish the appropriate confidence level of product performance. Various types of stress cycling are reviewed and correlated to damage mechanisms. Also discussed is the need for developing a strategy which includes a test plan, sampling methodology, test vehicles, and failure mode analysis.

• Appendix A, “Step-by-Step Example”

This section shows illustrations of applying the principles detailed in the information provided in this publication. Numerical examples are provided that highlight the relationship of the various parameters.

• Appendix B, “References”

This section provides reference to published information that has a bearing on solder joint reliability and is referenced in the body of the text of this document. Details are shown as to Title, Author, and Publisher.

• Appendix C, “Bibliography”

This section provides references to additional published information that could be of use to the practitioner. The references are organized into three major categories:

- 1) Accelerated Life Testing
- 2) Solder Joint Metallurgy and Etching
- 3) Vibration and Shock.

2.0 APPLICABLE DOCUMENTS

The following documents, of the issue currently in effect, form a part of this specification to the extent specified herein.

2.1 IPC¹

IPC-T-50 Terms and Definitions for Interconnecting and Packaging Electronic Circuits

IPC-PC-90 General Requirements for Implementation of Statistical Process Control

IPC-TM-650 Test Methods Manual

IPC-ET-652 Guidelines and Requirements for Electrical Testing of Unpopulated Printed Boards

IPC-R-700 Suggested Guidelines for Modification, Rework, and Repair of Printed Boards and Assemblies

IPC-TA-720 Technology Assessment of Laminates

IPC-SM-782 Surface Mount Land Patterns (Configurations and Design Rules)

IPC-SM-786 Recommended Procedures for Handling of Moisture Sensitive Plastic IC Packages

IPC-MS-810 Guidelines for High Volume Microsection

IPC-S-816 SMT Process Guideline & Checklist

2.2 Joint Industry Standards¹

J-STD-001 Requirements for Soldered Electrical and Electronic Assemblies

J-STD-002 Solderability Tests for Component Leads, Terminations, Lugs, Terminals and Wires

J-STD-003 Solderability Tests for Printed Boards

2.3 Military

MIL-HDBK-217

MIL-STD-810

2.4 Other Publications

American Society for Testing and Materials

ASTM E340-68 Standard Methods for Macroetching Metals and Alloys

ASTM E407-70 Standard Methods for Microetching Metal and Alloys

International Tin Research Institute

ITRI Pub #580 Metallography of Tin and Tin Alloys

ITRI Pub #708 Metallurgy of Solder Joints in Electronics

3.0 REQUIREMENTS

The reliability of the solder joint attachment of electronic components surface mounted to circuit board substrates requires explicit attention in the design phase, as well as during manufacturing. During use, surface mount (SM) solder joints can be subjected to a variety of loading conditions which can lead to premature failure if inadequately designed. The following loading conditions could exist either singly, sequentially or simultaneously:

- a) cyclic differential thermal expansion,
- b) vibration (transport),
- c) thermal shock (rapid temperature change causing transient differential warpages) during cooling from soldering operation or from severe use environments,
- d) mechanical shock (high acceleration) from severe use conditions or accidental misuse.

While vibration, thermal shock and mechanical shock are possible in practical applications, they are the exceptions rather than the norm; the failure mechanism of primary concern for SM solder joint reliability is cyclic differential thermal expansion/contraction causing fatigue damage. It should be noted that the resistance against failures induced by vibration fatigue, thermal shock and mechanical shock depends primarily on solder joint strength; this is not the case, however, for thermal fatigue failure resistance.

These thermal expansion differences result from changing temperatures due to power dissipation internal to the component and differences in the coefficients of thermal expansion (CTE) in combination with system internal or external temperature variations caused by component or system load fluctuations or on/off cycles, by diurnal cycles, or by seasonal changes. During operation, SM solder joints can be subjected to considerable cyclic strains caused by different thermal expansions of:

1. The surface mounted components and the substrates to which they are solder-attached.
2. The solder and the materials (component, lead, substrate) to which it is bonded.

To ascertain that the solder joint attachment of SM circuit assemblies meet reliability expectations in their intended use environments, it is necessary to produce a generic reliability data base using accelerated fatigue tests and to confirm the reliability for some specific applications. Because

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of the time dependent creep and stress relaxation properties of solder, the cyclic damage and the fatigue life in accelerated testing are not generally equivalent to those in operational use. Thus, to utilize the results from accelerated fatigue tests, an acceleration transform is necessary. This allows valid comparisons of results from different accelerated test conditions and more importantly, allows the extrapolation of these accelerated test results to predict the reliability of the product in use.

3.1 Terms and Definitions Terms and definitions used herein are in accordance with IPC-T-50, except as otherwise specified.

Note: Any definition denoted with an asterisk (*) is a reprint of the definitions in IPC-T-50.

3.1.1 Accelerated Reliability Test A test in which the damage mechanism(s) of concern for operational use is (are) accelerated to cause failures in less time than in service. The test acceleration results from shorter cycle periods and/or more severe loading conditions; however, the introduction of extraneous damage mechanisms must be avoided. The service life can be characterized by application of appropriate acceleration factors or transforms.

3.1.2 Acceptable Cumulative Failure Probability Maximum percentage of defectives/failures at the end of the service life within acceptable limit.

3.1.3 Bathtub Curve Methodology for quantifying reliability when the failure rate is plotted against time. The result often follows a pattern of failure known as a bathtub curve. Three periods are apparent. These periods differ in the frequency of failure and in the failure causation pattern.

3.1.4 Burn-In Test A test in which finished product is routinely subjected to normal, perhaps worst-case but still realistic, operational environments. In purpose it resembles the shakedown cruise of a ship. Burn-in is not an accelerated reliability test.

3.1.5 Creep The time-dependent visco-plastic deformation as a function of applied stress.

3.1.6 Coffin-Manson Model A predictive model which relates the number of cycles to failure to the applied plastic strain.

3.1.7 Cyclic Differential Expansion Expansion differences developed due to the differences in coefficients of thermal expansion and cyclic temperature changes during operational use or temperature cycling tests.

3.1.8 Cyclic Temperature Range/Swing Temperature amplitude between maximum and minimum temperatures occurring in operational service cycles or temperature cycling tests.

3.1.9 Design Service Life Fully functional duration of operation of a piece of equipment which is exposed to expected environment conditions.

3.1.10 Environmental Stress Screening (ESS) A screening procedure employing environmentally generated stresses to cause overstressing of 'weak' elements of an assembly to the point of failure to prevent these latent defects from reaching field service and possibly causing field failures. The environments producing these stresses may, or may not, be related to environmental conditions experienced by the product during service. Once having failed, the elements can be detected and either repaired, replaced, or discarded; and perhaps redesigned for future product. ESS needs to be accomplished without significant damage to the 'normal' elements of the assembly. ESS is not an accelerated reliability test.

3.1.11 Expected Design Life Life intended for a product by its designer.

3.1.12 Fatigue Ductility Exponent Exponent used in the Coffin-Manson low-cycle fatigue model to define the characteristic slope of the curve defining cyclic life versus cyclic visco-plastic strain energy.

3.1.13 Highly Accelerated Stress Testing (HAST) A stress test used to simulate corrosion related failures mechanisms under electrical bias while subjected to an accelerated stress combination of temperature and humidity. HAST may be used in the context of components and assemblies, but is not an accelerated reliability test for solder attachment.

3.1.14 Hysteresis Loop A diagram of the stress-strain behavior of solder joints obtained during a loading cycle from zero to a positive maximum, to zero to a negative maximum, and back to zero—the area of the hysteresis loop is a measure of the fatigue damage per cycle.

3.1.15 Infant Mortality Failure during burn-in, initial functional testing, and/or early in service associated primarily with manufacturing process or quality related problems.

3.1.16 Limp Home Capability Ability of equipment to function at a minimum level despite limited internal functional failures.

3.1.17 Manson-Coffin Plot A graphic representation which relates the number of cycles to failure to the applied plastic strain for both plastic and elastic behavior of a material.

3.1.18 Maximum Cyclic Strain Range The total strain range experienced after complete stress relaxation during exposure to cyclically induced thermal or mechanical deformations.



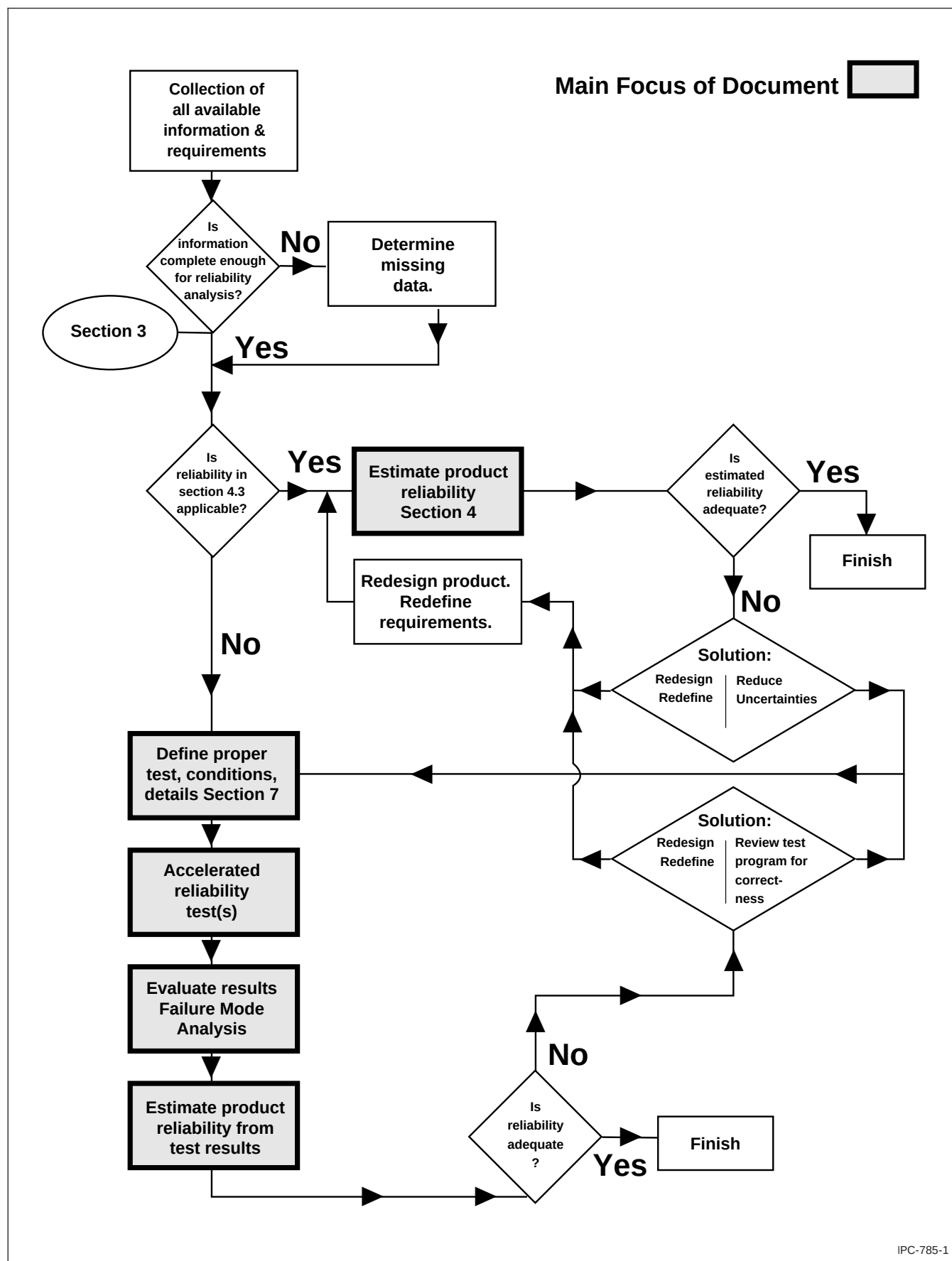


Figure 1 Flowchart for reliability

3.1.19 Mean Fatigue Life The life at which one-half of a given sample of items has failed.

3.1.20 Mechanical Shock A rapid transfer of mechanical energy to a system, which results in a significant change in stress, velocity, acceleration, or displacement within the system.

3.1.21 Process Qualification A special test(s) performed to validate a process capability in terms of producing a product capable of meeting performance specifications.

3.1.22 Process Verification Ongoing evaluation of processes involved in the manufacturing of a product to assure process optimization or to eliminate process deviations.

3.1.23 Random Steady State Period of useful operational life during which failures occur seemingly at random at a low rate weakly related to product complexity.

3.1.24 Reliability The ability of a product to function under given conditions and for a specified period of time without exceeding an acceptable failure level.

3.1.25 Solder Attachment The collection of solder joints (solder connections) associated with a component.

3.1.26 Stress Relaxation The time-dependent decrease in stress due to the visco-plastic deformation as a function of applied displacement.

3.1.27 Thermal Cycling (See 3.4.1) Exposure of assemblies to cyclic temperature changes where the rate of temperature change is slow enough to avoid thermal shock.

3.1.28 Thermal Shock (See 3.4.3) Exposure of assemblies to rapid changes of temperatures causing transient temperature gradients, warpages, and stresses. As a rule of thumb, rates of temperature change in excess of 30°C/minute are required.

3.1.29 Vibration A periodic, typically elastic, motion of a structure in alternately opposite directions from the position of equilibrium.

3.1.30 Visco-Plastic Strain Energy Density A measure of the total energy input into a cyclically loaded structure defined by the boundaries of a hysteresis loop for the applied stress versus strain over a single load cycle.

3.1.31 Wearout The process where the occurrences of failures rise steadily as the product deteriorates due to accumulating (fatigue) damage.

3.1.32 Weibull Distribution A statistical description of the distribution of product failure primarily useful in wearout situations.

3.2 Reliability Concepts and Understanding In the context of this document it is important to have a working definition of reliability:

Reliability is the ability of a product (for this document the products are surface mount solder attachments) to function under given conditions and for a specified period of time without exceeding acceptable failure levels.

Implicit in this definition is the fact that the reliability of SM solder joints is determined by wearout (fatigue), i.e., on a time-to-failure plot (the “bathtub curve”). Figure 2 shows individual “bathtub” reliability plots for SM solder attachments and for a “typical” electronic component without the solder attachment. Figure 3 shows the same information in the form of cumulative failure probability plots for the component and the SM solder attachment. The life of the solder attachment is primarily characterized by the right ascending part of the curve, where the failure rate rapidly increases with time due to wearout. This directly implies that manufacturing quality cannot increase the inherent reliability of a design in a given use environment; however, inadequate manufacturing quality can reduce this inherent designed-in reliability by increasing infant mortality failures.

Manufacturing introduces variability into the product. This variability encompasses ranges of all the properties for all the materials in the product, ranges in the dimensions of parts due to tolerance, compositional variations and non-homogeneities, fluctuations in processing parameters, etc. In good quality manufacturing these variabilities are controlled within ranges that will not significantly degrade product performance. Manufacturing of lesser quality can introduce larger variabilities and/or defects, which can significantly reduce product performance.

Superimposed on these product variabilities (materials, processing, etc.) are differences in the actual use environment, as well as reliability (fatigue) distributions. Even product that is nominally identical when subjected to identical loading conditions will show a statistical failure distribution. Since accelerated reliability testing is time-consuming and costly, it is typically carried out on a rather small number of samples. To capture representative product variabilities and their effect on reliability requires the testing of a sufficiently large number of samples to include these variables. The controlled introduction of artificially created defects that are assumed to have a significant reliability impact would serve the same purpose but is difficult to achieve in practice.



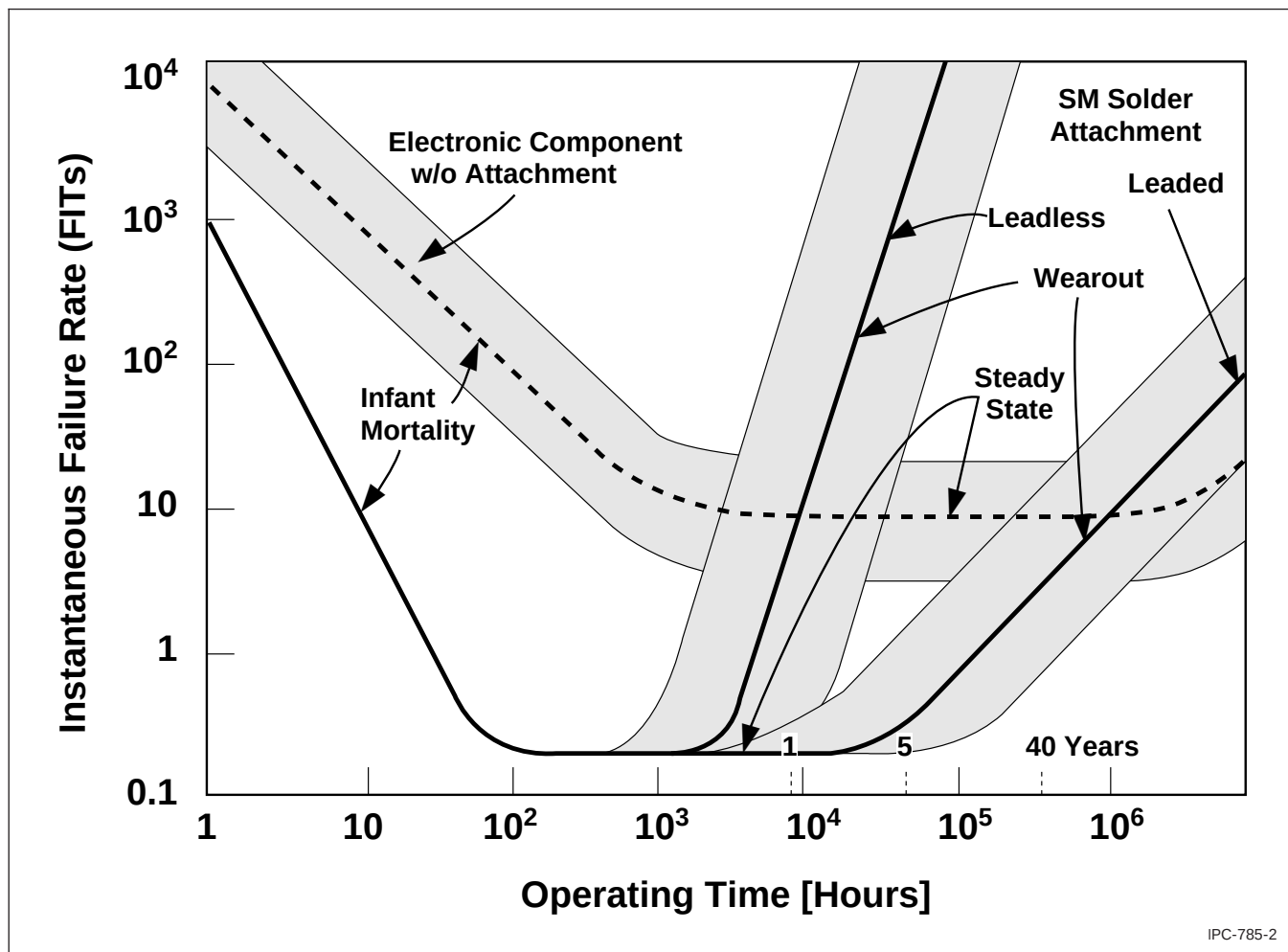


Figure 2 Generic reliability "bathtub" curves comparing electronic components and surface mount solder attachment

The reliability "bathtub" curves in Figure 2, as well as the resulting cumulative failure probability plots shown in Figure 3, need some explanation. The "infant mortality," "random steady-state," and "wearout" regions are defined by which of these three failure modes dominate. The curve intersections in Figure 2 delineate the extent of these regions.

Except for the SM solder attachment wearout regions, the values plotted are rather "soft." Hard data does not exist in adequate quantities for either the component or solder attachment "infant mortality" and "random steady-state" regions. These plot regions are based on experience and observed trends and some published information. The "steady-state" region for components depends to a large extent on the complexity of the component; chip components would fail well below the indicated bathtub band and very complex, high I/O chip carriers would fail at higher rates.

For SM solder attachment, no evidence exists that shows that the "random steady-state" failure region even exists; it is entirely possible that "infant mortality" and "wearout" form the entire failure rate history. It should be noted that

for SM solder attachments, the "infant mortality" and "random steady-state" failure regions are rather unimportant since the failure probabilities are very small even assuming order of magnitude errors. Significant however, is the experience-based observation that the "random steady-state" failure rate estimate given in MIL-HDBK-217 is too high by perhaps two or three orders of magnitude. Figures 2 and 3 imply that the reliability of electronic components is determined by the "random steady-state" failure region. In contrast, the reliability of the SM solder attachment is established by the "wearout" failure region.

The cumulative failure probability of a component and its SM solder attachment is the sum of the component and the attachment failure probabilities. Thus an electronic assembly is more likely to fail due to component failure in the short-term and due to solder joint failure in the long-term.

3.3 Reliability Assurance Surface mount solder joint reliability requires explicit attention in the design phase as well as in manufacturing. An overview of the processes leading to reliability assurance is outlined in the Figure 4 flow chart.

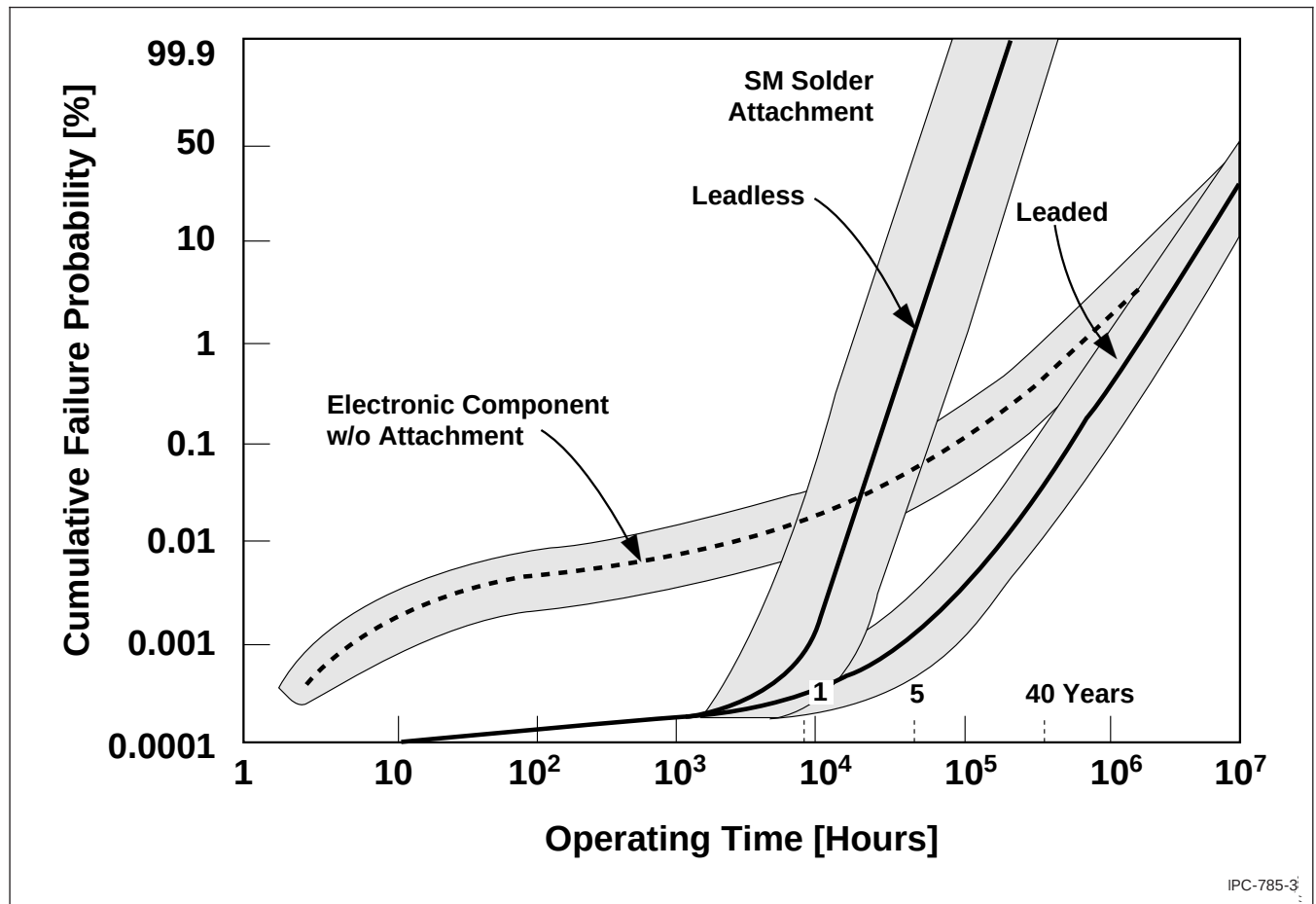


Figure 3 Generic cumulative failure probabilities for electronic component and surface mount solder attachment

3.3.1 Generic Understanding of Solder Attachment Technology Solder is unique due to its temperature-, time-, and stress-dependent behavior. For instance, eutectic tin-lead solder readily creeps and stress relaxes above 20°C, whereas below -20°C solder has long-term load bearing capabilities similar to other metals. The higher the temperature above 20°C and/or the higher the stress level, the faster the solder will creep and stress relax.

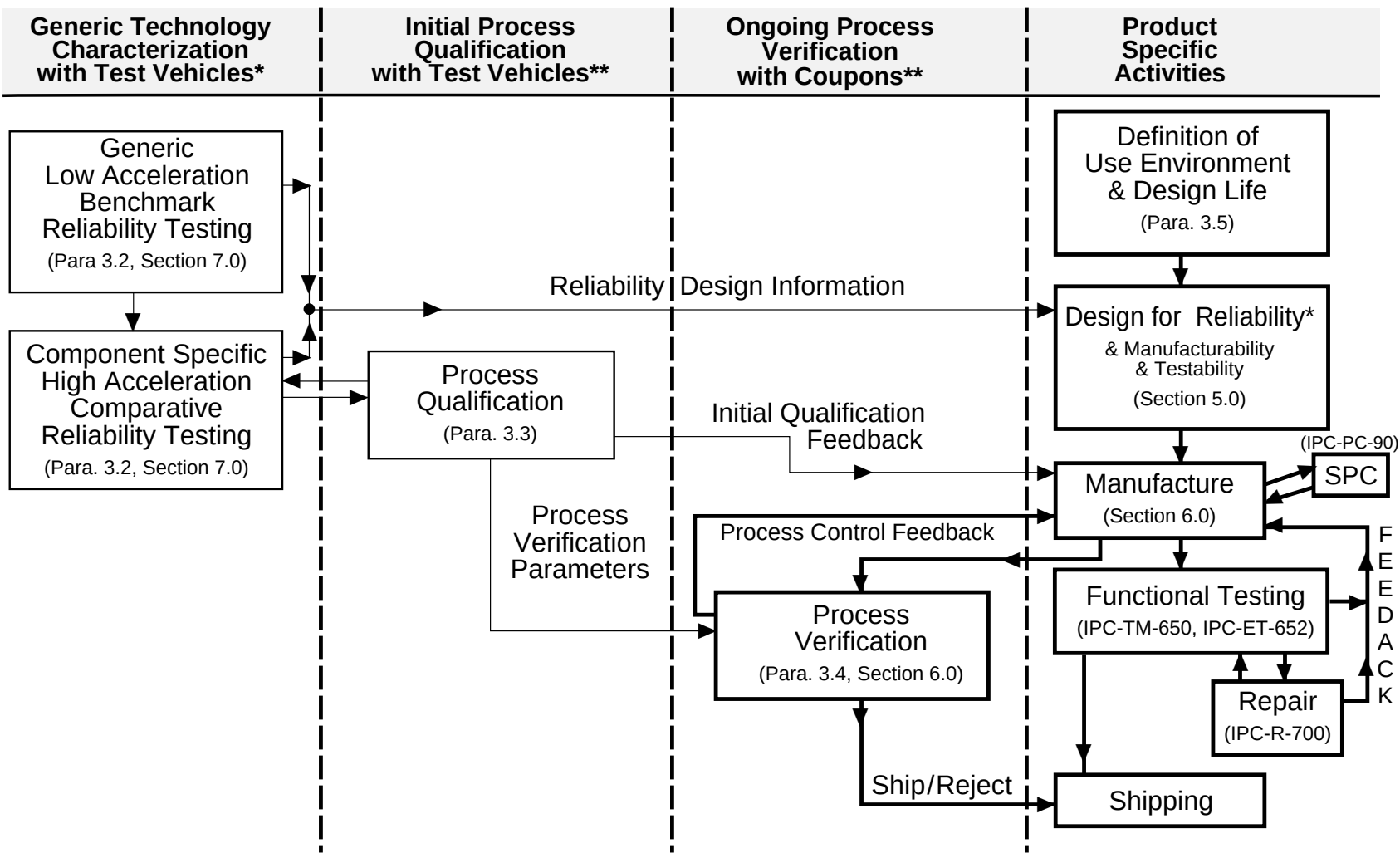
A generic understanding of the reliability and failure mechanisms for a given surface mount attachment technology is the first step toward designing and assuring product reliability. For this, a generic database is required. Although failure mechanisms based on cyclic or monotonic overstressing can occur, the most common reliability threat comes from stress-relaxation based fatigue damage. A fatigue failure database must be based on a combination of low acceleration and high acceleration tests.

In this context, low acceleration tests produce mean-times-to-failure of the test vehicles that are about 10 to 20 times shorter than actual life in field use. High acceleration tests are about 100 to 500 times shorter. The higher the test acceleration, the less the test results are representative of performance at field conditions. Thus, low acceleration tests should closely mimic expected field conditions,

whereas high acceleration tests are a “quick and dirty” compromise necessitated by the reality of the time and resources required for the low acceleration testing.

For accelerated tests, it is imperative that the failures occur as the result of accelerating the proper failure mechanisms. Thermal shock testing does not accelerate the long-term fatigue mechanisms of concern for most surface mount applications, and can result in misleading conclusions. The driving, underlying mechanism causing most of the long-term fatigue damage results from the creep and stress-relaxation behavior of solder. Therefore, accelerated fatigue testing must include well defined dwell times at the cycle extremes to allow for some, albeit incomplete, creep and stress relaxation. The incomplete cyclic creep and stress relaxation in accelerated test cycles is in contrast to most actual field operation environments, where sufficient time is usually available for essentially complete creep and stress relaxation. Thus, the significantly smaller fatigue damage for accelerated test cycles must be accounted for with a fatigue acceleration transform.

The low acceleration tests shown in the leftmost column of Figure 4 call for a highly accurate mimicking of use conditions, with acceleration factors of ten or twenty. For example, if the design life is twelve years, fatigue testing



*Also, see IPC-D-279 and IPC-SM-782. **Also, see IPC-TR-521 and IPC-PC-90.

IPC-785-4

Figure 4 Flow chart for surface mount solder attachment reliability assurance

can be accelerated to the point of completion in about one year. Low acceleration tests are necessary to provide generic, accurate, “benchmark” results.

High acceleration tests typically require isothermal mechanical cycling. These tests can provide acceleration factors up to about 500 for mean-time-to-failure (MTTF) for the test, relative to the field MTTF. This is accomplished by testing at elevated temperatures (above 20°C) and applying the cyclic loads mechanically. Mechanical cycling is necessary as the loading technique, because thermal cycling requires substantial transition times between the high and low temperature extremes in order to avoid thermal shock-induced failures not representative of the stress-relaxation fatigue failure mechanism. These high acceleration tests bear relatively little resemblance to use conditions, and the results are useful primarily for relative comparisons. However, by performing both high and low acceleration tests for comparable test vehicles, the low acceleration tests can serve as reliability benchmarks for the more highly accelerated tests. Thus, a limited number of the time consuming low acceleration tests, in combination with the much quicker high acceleration tests, can provide a complete database.

Although the reasons for microelectronic device failures are many, the major cause of failure for solder joints of surface mount components is low cycle thermal fatigue. High cycle fatigue due to vibration can also make some contribution to fatigue damage. Thus, the surface mount technology (SMT) solder joint failures are primarily due to the thermal/mechanical stresses.

The frequency of the thermal cycles for low cycle thermal fatigue usually ranges from a few cycles per hour to one cycle per day or less. The frequency range of equipment vibration is typically from between 10 Hz to 2000 Hz, which results in over one hundred thousand cycles per day. The fatigue damage in vibration is primarily in high-cycle fatigue.

3.3.2 Design The general understanding gained from the accelerated fatigue tests must be translated into reliability design information that can be used for “Design for Reliability.” The design information needs to be in the form of simple engineering tools that allow the non-expert designer to assess whether a design meets its reliability requirements. Prior to the “Design for Reliability” in the right-most column of Figure 4, the use environment, the expected design life, and the acceptable cumulative probability of failure at the end of this design life must be established.

3.3.3 Manufacturing Process Qualification The capability of the manufacturing process sequence to produce a reliable product needs to be established in the process qualification of production test vehicles. Some of the test

vehicles are run through high acceleration reliability testing and some through the verification process. This qualification activity is relatively complex due to the number and variety of processes used to manufacture and assemble electronic hardware.

Process control parameters and process capability identification are necessary to provide the link between reliability and consistent product. Since each manufacturer has unique combinations of processes, the process control and qualification are different for each manufacturer. In order to ensure that a process is well understood, a manufacturer should characterize those aspects of the process that have the most significant impact on product performance. A properly constructed “Design of Experiment,” which evaluates the key variables of the process including their interaction, is paramount to establishing process capability. IPC-PC-90 provides the requirements of the systematic path for establishing process capability. J-STD-001 provides the mechanism for evaluating performance to a strategic plan.

The “Process Qualification” step in the second column from the left in Figure 4 also establishes the process verification parameter windows which assure product consistency within the process qualification parameters.

3.3.4 Process Verification Many factors can affect the manufacturing process and may cause changes in the performance of the product in its intended application. A properly characterized process identifies the key variables and establishes the appropriate upper and lower control limits of those attributes which play a significant role on the quality and reliability aspects of the product. If the process changes, a value judgment is required to determine the significance of the change and to determine if the change is an expected variation, a noise factor, or an out-of-control condition.

Ongoing process verification using production boards, production test vehicles, or test coupons that represent the design concepts, together with statistical process control and touch-up/repair feedback, is needed as proof that the process is meeting its projected capability.

Monitoring of product performance through destructive and nondestructive evaluations verifies the relationship between the design, the design reliability expectations and the manufacturing processes.

Although no generic or standard process verification procedure has currently been identified which serves the purpose to an adequate degree, verification of the adequacy of the process is an ongoing activity. The frequency of testing and the type of tests invoked should be commensurate with the maturity of the design and the stability of the process.

3.4 Damage/Failure Mechanisms

3.4.1 Thermal Cycling Damage Mechanisms The primary damage mechanism in thermal cycling is the creep/stress-relaxation-enhanced fatigue of the solder joints. Figure 5 is a stylized representation of the visco-plastic strain energy, proportionally represented by the area of the cyclic hysteresis loops in a stress-strain diagram, expended in one fatigue cycle. This visco-plastic strain energy causes fatigue damage which accumulates from cycle to cycle. When loaded from a zero-stress, zero-strain condition, the solder joint first undergoes elastic deformation followed by plastic yielding if the loading continues beyond the yield strength of the solder. It has to be noted, however, that for solder there is neither a truly elastic deformation nor is the yield strength defined in any physically real sense. The elastic deformation-yielding lines are simplified linearizations of the non-linear stress-strain response that is highly dependent on temperature, loading rate, solder composition and grain structure. Further, the yield strength is a defined artifact for engineering purposes; its definition for solder is equally highly dependent on several variables some of which are controllable (i.e., temperature), and some which are not (i.e., grain structure).

The elastic-plastic yielding portion of the loading response is followed by a temperature- and stress-level-dependent stress relaxation/creep response of the solder joint. Given enough time, which can be minutes at the higher temperatures and days at the lower temperatures, the stresses in the attachment system, of which the solder joints are a part, will essentially completely relax resulting in the maximum possible plastic deformation strains in the solder joints. Dwells beyond this time will not induce further fatigue damage; however, at elevated temperatures the detrimental grain growth in the solder continues.

The primary complication in the damage mechanism arises from the fact that in many applications and, by definition, all accelerated tests, the dwell times are insufficient for complete stress relaxation. The effect of this is illustrated in Figure 5 in the hysteresis loops labeled "Accelerated Tests" for which the loop areas are significantly smaller than the corresponding loop areas for conditions allowing complete stress relaxation. This signifies considerably less fatigue damage per cycle for those accelerated cyclic environments. As a consequence, the number of accelerated test cycles cannot be directly equivalent to the number of operational cycles.

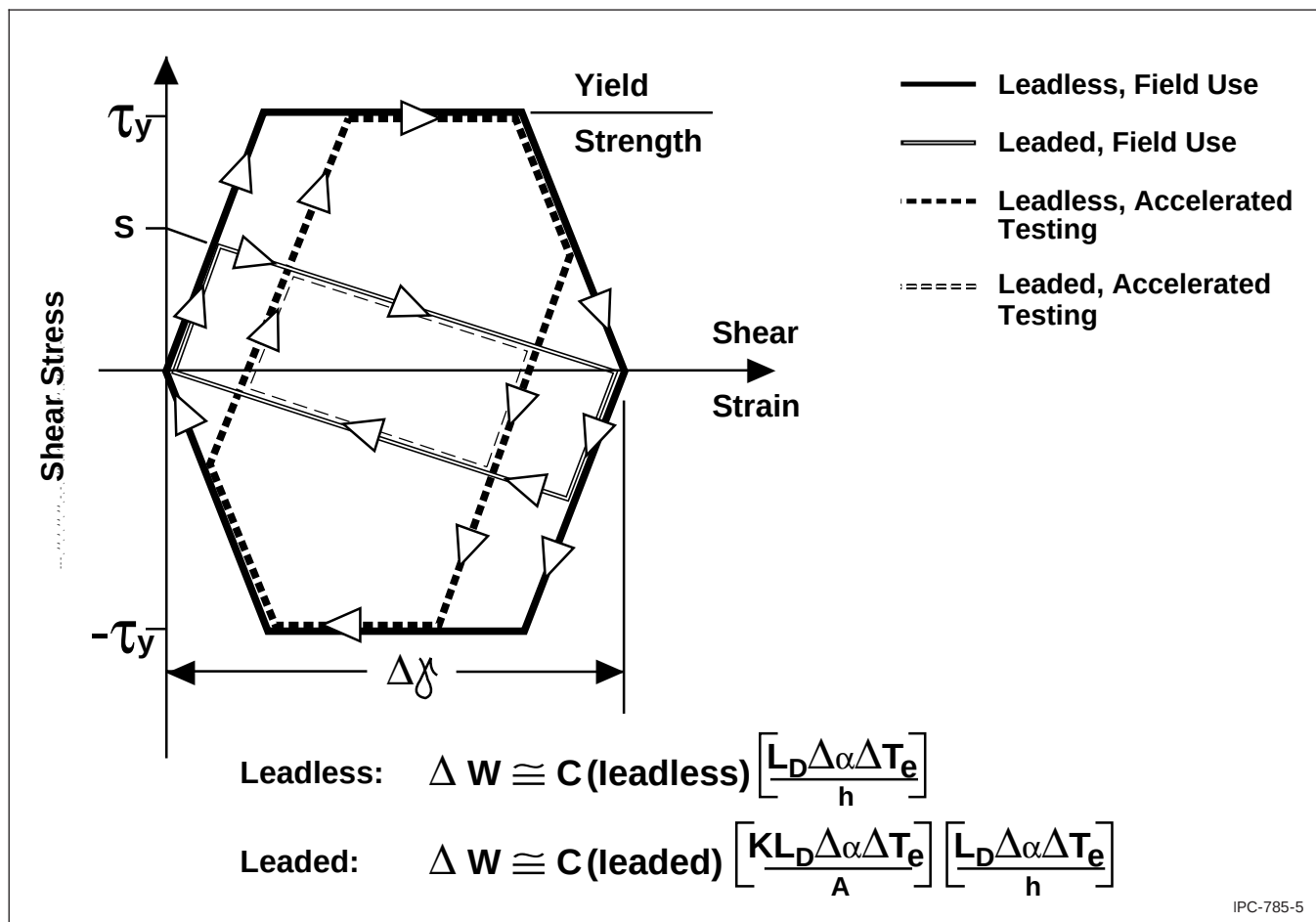


Figure 5 Cumulative fatigue damage

Figure 5 also shows the essential difference between stiff leadless solder attachments and compliant leaded SM attachments. Compliant leaded attachments work because the lead compliancy keeps the maximum stresses in the solder joints significantly below the “yield strength.” It should be noted that not all leads are compliant in this context. The diagonal lead stiffness should be below 100 lb/in; above this value, leaded SM attachments become an undefined hybrid between leadless and compliant leaded attachments. While the lead compliance effects complicate the analysis, they substantially reduce the accumulating cyclic fatigue damage even for identical strains at complete stress relaxation. Given the stress-level dependence of the stress relaxation rate and the lower stress levels for solder joints with compliant leads, complete stress relaxation for compliant leaded solder attachment takes significantly longer.

It should be noted that symmetric hysteresis loops as shown in Figure 5 are possible in thermal cycling only if the low temperature dwell times are significantly longer than the high temperature dwells; symmetry, however, is typical for isothermal cycling where the loads are mechanically induced.

The solder joint behavior described in Figure 5 pertains to temperature cyclic environments above about -20°C . The temperature region from about -20 to $+20^{\circ}\text{C}$ is the boundary between primarily a creep/stress relaxation response of the solder to applied loads at the higher temperatures, and a primarily stress-driven solder response at the lower temperatures. The damage mechanism described in Eqs. 3 and 4 is for temperature cyclic environments above about -20°C , which are the more typical use conditions.

For applications in which the stress relaxation and creep in the solder joint is not the dominant mechanism, such as low temperature applications with component operating temperatures of less than 0°C and/or high thermal/mechanical frequency application with frequency of greater than 0.5 Hz or half cycle dwell times of less than 1 second, the direct application of the Coffin-Manson fatigue relationship (see Section 4.3.5) is advised.

Solder joints seeing large temperature swings significantly through the temperature region from -20 to $+20^{\circ}\text{C}$, in which the change from stress-to-strain driven solder response takes place, do not follow the damage mechanism described in Eqs. 3 and 4 [1]. The damage mechanism is different than that for more typical use conditions and is likely dependent on overstress and recrystallization considerations.

As the fatigue damage accumulates, the grain structure of the solder joints coarsens. After about 25 to 50% of the fatigue life of the solder joints is consumed, microvoids or cavitations form at grain boundary intersections. These microvoids grow into microcracks which, with further accumulating fatigue damage, grow and coalesce into large

cracks. For solder joints experiencing non-uniform strain and stress distributions, such as castellated solder joints, a single major crack will lead to failure. For solder joints with uniform strain and stress distribution, such as column-like joints, many multiple cracks will form with one finally failing first.

3.4.2 Vibration Damage Mechanism Vibration induced failures of surface mount solder joints are fundamentally different from thermally induced failures. During thermal cycling, the solder joint is loaded by thermal expansion mismatch. The solder joint strains are dominated by plastic behavior induced by stress relaxation during the cycle hold time. In contrast, vibrations at relatively high frequencies (over 30 Hz), result in elastic behavior in the joint. Stresses are generally smaller and failure occurs over many cycles in the same manner as classic high cycle fatigue in structures.

Vibrations are periodic motion of a body about an equilibrium position. This type of motion is encountered in many applications including automotive, aerospace and military applications. Consequently, electronic enclosures or structures utilized in these environments are also subjected to vibration. Vibrations are transmitted to the printed circuitry through the chassis or primary structure of the enclosure. Relative motion between the board and its edge brackets result in deflections of the board. The stresses induced in surface mounted solder joints are primarily a function of the radius of curvature of the board occurring as a result of the deflection and the position of the part on the board.

Generally, the magnitude of the stresses or cyclic stress amplitude induced by vibration are relatively small. This in combination with the high frequency motion or high strain rates induce elastic behavior in the joint. The rapidly changing loads do not allow for stress relaxation. In addition, the elastic modulus of solders tends to increase with increasing frequency of loading or increasing strain rates. This favors elastic behavior.

However, very high stresses can be induced in solder joints under certain conditions. If the frequency of the external driving force approaches the natural frequency of the board, large board deflections will occur. Hence, large stresses will be induced in joints at certain board locations. The natural frequency is simply the frequency at which the system will vibrate under free conditions. When the external driving frequency approaches this frequency a resonant condition occurs. Generally, electronic equipment is tested over a frequency range representative of the application to ensure there are no undesirable resonant frequencies inherent in the design.

Although the bulk stresses are elastic, failure occurs due to highly localized plastic behavior. Small stress concentrations or defects on the surface of the solder or at interfaces induce localized plastic strains. At solder joints, the

structure of individual “grains” of the solder is oriented so that maximum applied shear stresses exceed the critical stress necessary to induce slip in easy slip planes. Under cyclic loading conditions intrusions and extrusions occur. Eventually well formed intrusions or persistent slip bands form microcracks.

The microcracks grow and coalesce into one larger crack. Crack propagation is generally transgranular as opposed to “intergranular” cracking observed in creep dominated thermal fatigue. Stable crack growth occurs by striation formation until the joint can no longer withstand the applied load. Failure of the joint subsequently occurs when the joint is no longer structurally and electrically viable. This process generally occurs in a large number of cycles (10^4 or greater) and is termed high-cycle fatigue as opposed to low-cycle fatigue (10^3 cycles or less) resulting from cyclic strain amplitudes large enough to cause substantial plastic yielding strains; the range in between is a mixed mode.

3.4.3 Thermal Shock Damage Mechanism In thermal shock, the extremely rapid temperature changes (about $30^\circ\text{C}/\text{minute}$ and above) result in warping of the surface mount assembly. The warpage is caused by large transient thermal gradients induced by the rapid temperature change when the boards are plunged into a new thermal environment. The warpages result in tensile and shear stresses where the tensile loading dominates over the steady state expansion mismatch. Thus, even assemblies with matched coefficients of thermal expansion will exhibit solder joint failures when subjected to thermal shock. The thermal shock loading mechanism is summarized in Figure 6.

Thermal shock conditions can arise from several sources. Examples of these are as follows:

1. Rapid changes in external environment, e.g., sun-to-shade in space.
2. Sudden and large changes in power status.
3. Various manufacturing/repair processes, e.g., reflow, vapor decrease, rework, repair, etc.

The distinction between thermal shock and thermal cycling is not always addressed in designing reliability experiments. There is a fundamental difference between thermal shock and thermal cycling. The primary differences arise from the mechanism of loading. Thermal shock tends to result in multiaxial states of stress dominated by tensile over stresses and tensile fatigue. On the other hand, as previously discussed, thermal cycling results in shear loads and failure occurs from an interaction of shear fatigue and stress relaxation. Thermal shock is performed in dual chamber test equipment whereas thermal cycling is performed in single chamber cycling equipment. Dual chamber arrangements may produce temperature transition rates in excess of $50^\circ\text{C}/\text{minute}$.

Most single chambers generally do not produce transition rates even close to $30^\circ\text{C}/\text{minute}$ which is roughly the mini-

mum rate necessary to induce thermal shock. The results of these two types of testing are generally not correlatable, even through some design measures will prolong life under both conditions. Consequently, thermal shock testing for purposes of evaluating surface mount solder joint reliability is only appropriate if thermal shock is indeed a field condition encountered by the product.

In some specifications, the definitions of thermal cycling and thermal shock are not fully differentiated; the rates of change are more closely associated with what we are calling thermal shock.

3.4.4 Creep Rupture of Solder Joints Creep rupture refers to a condition in which a solder joint has a fixed load applied to it. The application of the load creates an initial deflection in the solder joint. As time increases, the solder in the joint will creep. This results in an increase in deflection while the load on the sample remains constant. Creep rupture occurs when the solder cannot support the applied load any longer and fractures.

When the solder joint fractures in creep rupture, the time to failure can be plotted for a range of applied initial loads or deflections. The latter would be the condition the solder joint sees when components are soldered to a board and the board is put into a bent shape creating a constant strain on each solder joint. If the board remains in this bent shape, the solder joints could fracture in creep rupture. Analysis of the fracture surface would most likely show the usual ductile rupture/fracture surface characteristic of solder.

While creep rupture is similar to stress relaxation in terms of the underlying mechanism, stress relaxation is the condition that occurs when the solder joint is subjected to a fixed deflection. As time increases, the stresses in the solder joint undergo relaxation, but the deflection remains constant. The decrease in load at fixed deflection results in the elastic strains in the solder joint being converted into plastic permanent strains.

3.5 Application Considerations The reliability of a surface mount assembly is dependent on the service environment, the expected cyclic service life, and the acceptable cumulative failure probability at the end of the cyclic service life. The reliability of a surface mount attachment, of course, also depends on the assembly design parameters (including the number and mix of components), which will be dealt with in the section on Design for Reliability.

3.5.1 Service Environment In Table 1 worst-case, but realistic, use environments for SM electronic assemblies are shown in nine major use categories. These use environment categories are listed in order of increasing severity without consideration of the number of expected service years. It should be noted that the cyclic temperature range, ΔT , is not the difference between the possible