



ASSOCIATION CONNECTING
ELECTRONICS INDUSTRIES®

IPC-9701A

Performance Test Methods and Qualification Requirements for Surface Mount Solder Attachments

IPC-9701A

February 2006

A standard developed by IPC

Supersedes IPC-9701
January 2002

3000 Lakeside Drive, Suite 309S, Bannockburn, IL 60015-1219

Tel. 847.615.7100 Fax 847.615.7101
www.ipc.org



Documents
Document Sharing Hub

The Principles of Standardization

In May 1995 the IPC's Technical Activities Executive Committee (TAEC) adopted Principles of Standardization as a guiding principle of IPC's standardization efforts.

Standards Should:

- Show relationship to Design for Manufacturability (DFM) and Design for the Environment (DFE)
- Minimize time to market
- Contain simple (simplified) language
- Just include spec information
- Focus on end product performance
- Include a feedback system on use and problems for future improvement

Standards Should Not:

- Inhibit innovation
- Increase time-to-market
- Keep people out
- Increase cycle time
- Tell you how to make something
- Contain anything that cannot be defended with data

Notice

IPC Standards and Publications are designed to serve the public interest through eliminating misunderstandings between manufacturers and purchasers, facilitating interchangeability and improvement of products, and assisting the purchaser in selecting and obtaining with minimum delay the proper product for his particular need. Existence of such Standards and Publications shall not in any respect preclude any member or nonmember of IPC from manufacturing or selling products not conforming to such Standards and Publication, nor shall the existence of such Standards and Publications preclude their voluntary use by those other than IPC members, whether the standard is to be used either domestically or internationally.

Recommended Standards and Publications are adopted by IPC without regard to whether their adoption may involve patents on articles, materials, or processes. By such action, IPC does not assume any liability to any patent owner, nor do they assume any obligation whatever to parties adopting the Recommended Standard or Publication. Users are also wholly responsible for protecting themselves against all claims of liabilities for patent infringement.

IPC Position Statement on Specification Revision Change

It is the position of IPC's Technical Activities Executive Committee that the use and implementation of IPC publications is voluntary and is part of a relationship entered into by customer and supplier. When an IPC publication is updated and a new revision is published, it is the opinion of the TAEC that the use of the new revision as part of an existing relationship is not automatic unless required by the contract. The TAEC recommends the use of the latest revision. Adopted October 6, 1998

Why is there a charge for this document?

Your purchase of this document contributes to the ongoing development of new and updated industry standards and publications. Standards allow manufacturers, customers, and suppliers to understand one another better. Standards allow manufacturers greater efficiencies when they can set up their processes to meet industry standards, allowing them to offer their customers lower costs.

IPC spends hundreds of thousands of dollars annually to support IPC's volunteers in the standards and publications development process. There are many rounds of drafts sent out for review and the committees spend hundreds of hours in review and development. IPC's staff attends and participates in committee activities, typesets and circulates document drafts, and follows all necessary procedures to qualify for ANSI approval.

IPC's membership dues have been kept low to allow as many companies as possible to participate. Therefore, the standards and publications revenue is necessary to complement dues revenue. The price schedule offers a 50% discount to IPC members. If your company buys IPC standards and publications, why not take advantage of this and the many other benefits of IPC membership as well? For more information on membership in IPC, please visit www.ipc.org or call 847/597-2872.

Thank you for your continued support.



ASSOCIATION CONNECTING
ELECTRONICS INDUSTRIES®

IPC-9701A

Performance Test Methods and Qualification Requirements for Surface Mount Solder Attachments

Developed by the SMT Attachment Reliability Test Methods Task Group
(6-10d) of the Product and Reliability Committee (6-10) of IPC

Supersedes:

IPC-9701 - January 2002

Users of this publication are encouraged to participate in the
development of future revisions.

Contact:

IPC
3000 Lakeside Drive, Suite 309S
Bannockburn, Illinois
60015-1219
Tel 847 615.7100
Fax 847 615.7105



Acknowledgment

Any document involving a complex technology draws material from a vast number of sources. While the principal members of the SMT Attachment Reliability Test Methods Task Group (6-10d) of the Product and Reliability Committee (610) are shown below, it is not possible to include all of those who assisted in the evolution of this standard. To each of them, the members of the IPC extend their gratitude.

Product and Reliability Committee	SMT Attachment Reliability Test Methods Task Group	Technical Liaisons of the IPC Board of Directors
Chair Reza Ghaffarian, Ph.D Jet Propulsion Laboratory	Chair Reza Ghaffarian, Ph.D Jet Propulsion Laboratory	Peter Bigelow IMI Inc.
Vice-Chair Werner Engelmaier Engelmaier Associates, L.C.	Vice-Chair Werner Engelmaier Engelmaier Associates, L.C.	Sammy Yi Flextronics International Sanmina

SMT Attachment Reliability Test Methods Task Group

Mudasir Ahmad, Cisco Systems, Inc.	Jennie Hwang, Ph.D., Asahi America, Inc.	Brett Ong, Sun Microsystems, Inc.
Patricia J. Amick, Boeing Aircraft & Missiles	Vincent B. Kinol, Umicore America Inc.	Michael D. Osterman, University of Maryland
David Baker, Tessera, Inc.	Gregg Klawson, General Dynamics - C4 Systems	Deepak K. Pai, C.I.D.+, General Dynamics-Advanced Information
Jean Bobgan, Guidant Corporation	Kuan-Shaur Lei, Hewlett-Packard Company	S.Y. Pai, Xilinx, Inc.
Nicole Butel, Agilent Technologies	James F. Maguire, Intel Corporation	Mel Parrish, STI Electronics, Inc.
Srinivas Chada, Ph.D, Jabil Circuit, Inc.	Wesley R. Malewicz, Draeger Medical Systems, Inc.	Kumar Pavuluri, Texas Instruments Inc.
Beverley Christian, Ph.D., Research In Motion Limited	John Manock, Lucent Technologies, Inc.	Vincent M. Rogers, IBM Corporation
Jean-Paul Clech, EPSI	Susan S. Mansilla, Robisan Laboratory Inc.	Olli Salmela, Nokia Corporation
Thomas Clifford, Lockheed Martin Space Systems Company	Brian C. McCrory, Delsen Testing Laboratories	Sundar Sethuraman, Soletron Corporation
Roger Cox, Key Tronic Corporation	Stephan Meschter, Ph.D., BAE Systems Platform Solutions	Rocky Shih, Hewlett-Packard Company
Howard S. Feldmesser, Johns Hopkins University	Frank Mortan, Texas Instruments	Vern Solberg, Mico Electronic Engineering Services
Mahendra S. Gandhi, Northrop Grumman	John Moylan, Delsen Testing Laboratories	Vasu S. Vasudevan, Intel Corporation
Luke J. Garner, Intel Corporation	Keith G. Newman, Sun Microsystems Inc.	Dewey Whittaker, Honeywell Inc.
Phil Geng, Intel Corporation		Leilei Zhang, Xilinx, Inc.
Denis Gignac, Nortel Networks		
Hana Hsu, Mitac International Corporation		



Table of Contents

1 SCOPE	1	3.4.21 Wearout Failures	5
1.1 Purpose	1	3.5 Statistical Failure Distribution Concepts	6
1.2 Performance Classification	1	3.5.1 Statistical Failure Distribution	6
1.3 Definition of Terms	1	3.5.2 Mean Fatigue Life, $N(50\%)$	6
2 APPLICABLE DOCUMENTS	1	3.5.3 Failure Free Life, N_0	6
2.1 IPC	1	3.5.4 Cumulative Failure Percentage	6
2.2 Joint Industry Standards	2	3.5.5 Cumulative Failure Probability	6
2.3 International Tin Research Institute	2	3.5.6 Acceptable Cumulative Failure Probability	6
2.4 Other Publications	2	3.6 Reliability Tests	6
2.4.1 Electronic Industries Association	2	3.6.1 Accelerated Reliability Test	6
2.4.2 OEM Working Group	2	3.6.2 Thermal Cycling	6
3 TERMS, DEFINITIONS AND CONCEPTS	2	3.6.3 Thermal Shock	6
3.1 General	2	3.6.4 Power Cycling	6
3.2 Reliability Concepts	2	3.7 Other Tests	6
3.2.1 Reliability Definition	3	3.7.1 Burn-In Test	6
3.3 Physics-of-Failure Concepts	3	3.7.2 Environmental Stress Screening (ESS)	6
3.3.1 Creep	3	3.7.3 Highly Accelerated Stress Testing (HAST)	6
3.3.2 Stress Relaxation	3	3.7.4 Mechanical Shock	6
3.3.3 Solder Creep-Fatigue Model	3	3.7.5 Vibration	7
3.3.4 Differential Thermal Expansion	3	3.7.6 Process Qualification	7
3.4 Test Parameters	3	3.7.7 Process Verification	7
3.4.1 Working Zone	3	3.8 Evaluation and Application Considerations	7
3.4.2 Cyclic Temperature Range/Swing	3	3.9 Understanding of Solder Attachment Technology	7
3.4.3 Sample Temperature: T_s	5	4 PERFORMANCE TEST METHODS	7
3.4.4 Maximum Sample Temperature: T_s (max)	5	4.1 General Requirements	7
3.4.5 Maximum Nominal Temperature: T (max)	5	4.2 Test Vehicles	7
3.4.6 Minimum Sample Temperature: T_s (min)	5	4.2.1 Component Description	7
3.4.7 Minimum Nominal Temperature: T (min)	5	4.2.2 Printed Wiring (Circuit) Boards	10
3.4.8 Mean Cyclic Temperature, T_{SJ}	5	4.2.3 Board Assembly	11
3.4.9 Nominal ΔT	5	4.3 Accelerated Temperature Test Methods	12
3.4.10 Dwell/Soak Time, t_D	5	4.3.1 Preconditioning by Isothermal Aging	12
3.4.11 Dwell/Soak Temperature	5	4.3.2 Temperature Cycling	12
3.4.12 Cycle Time	5	4.3.3 Test Monitoring	12
3.4.13 Temperature Ramp Rate	5	5 QUALIFICATION REQUIREMENTS	13
3.4.14 Maximum Cyclic Strain Range	5	5.1 Thermal Cycling Ranges	13
3.4.15 Maximum Cyclic Stress Range	5	5.2 Thermal Cycling Test Durations	14
3.4.16 Hysteresis Loop	5	5.3 Number of Samples	14
3.4.17 Design Service Life	5	5.4 Test Exemption Requirements	14
3.4.18 Projected Service Life Service	5	6 FAILURE ANALYSIS	14
3.4.19 Infant Mortality Failures	5	6.1 Failure Analysis Procedures	14
3.4.20 Random Steady-State Failures	5	6.2 Failure Analysis Documentation Requirements	14



7 QUALITY ASSURANCE 14

7.1 Responsibility for Inspection 14

7.2 Quality Conformance Inspection 14

7.2.1 As Assembled Inspection 14

7.2.2 Thermal Cycling Inspection 15

7.2.3 Failure Analysis Inspection 15

APPENDIX A 16

APPENDIX B 18

Figures

Figure 3-1 Representative Temperature Profile for Thermal Cycle Test Conditions 3

Tables

Table 3-1 Product Categories and Worst-Case Use Environments for Surface Mounted Electronics 4

Table 4-1 Temperature Cycling Requirements 8

Table 4-2 Daisy Chain Requirements 8

Table 4-3 Test Exemption Requirements 9

Table 4-4 Test Monitoring Requirements 13

Table A-1 Values for Exponent “m” for the Four Test Condition Levels and for Four Representative Product Use Conditions 17

Table A-2 Mean Fatigue Lives for a Given Component Assembly for the Four Test Condition Levels and for Four Representative Product Use Conditions 17

Performance Test Methods and Qualification Requirements for Surface Mount Solder Attachments

1 SCOPE

This specification establishes specific test methods to evaluate the performance and reliability of surface mount solder attachments of electronic assemblies. It further establishes different levels of performance and reliability of the solder attachments of surface mount devices to rigid, flexible and rigid-flex circuit structures. In addition, it provides an approximate means of relating the results from these performance tests to the reliability of solder attachments for the use environments and conditions of electronic assemblies.

1.1 Purpose The purpose of this document is:

- To provide confidence that the design and the manufacturing/assembly processes create a product that is capable of meeting its intended goals.
- To permit the analytical prediction of reliability based on a generic database and technical understanding.
- To provide standardized test methods and reporting procedures.

1.2 Performance Classification This specification recognizes that surface mount assemblies (SMAs) will be subject to variations in performance requirements based on end use. While Performance Classes are defined in IPC-6011, *Generic Performance Specification for Printed Boards*, these performance classifications are not specific as to the required reliability. At this point in time, the reliability requirements need to be established by agreement between customer and supplier.

1.3 Definition of Terms The definition of all terms used herein **shall** be as specified in IPC-T-50, except as otherwise specified in Section 3.

1.4 Interpretation “**Shall**,” the imperative form of the verb, is used throughout this specification whenever a requirement is intended to express a provision that is mandatory. Deviation from a “**shall**” requirement may be considered if sufficient data is supplied to justify the exception.

The words “should” and “may” are used whenever it is necessary to express non-mandatory provisions. “Will” is used to express a declaration of purpose.”

To assist the reader, the word “**shall**” is presented in bold characters.

1.5 Revision Level Changes Changes made to this revision of the IPC-9701 include Appendix B which establishes guidelines for thermal cycle requirements for Pb-free solder joints. Appendix B provides additional recommendations to existing IPC-9701 section requirements when utilizing a Pb-free soldering process.

2 APPLICABLE DOCUMENTS

The following documents are applicable and constitute a part of this specification to the extent specified herein. Subsequent issues of, or amendments to, these documents will become a part of this specification. Documents are grouped under categories as IPC, Joint Industry Standard, ITRI, EIA and others depending on the source.

2.1 IPC¹

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

IPC-D-279 Design Guidelines for Reliable Surface Mount Technology Printed Board Assemblies

IPC-TM-650 Test Methods Manual²

- 2.1.1 Microsectioning
- 2.4.1 Adhesion, Plating
- 2.4.8 Peel Strength, Metal Foil
- 2.4.21.1 Bond Strength, Surface Mount Land (Perpendicular Pull Method)
- 2.4.22 Bow and Twist
- 2.4.36 Rework Simulation, Plated-Through Holes
- 2.4.41.2 Coefficient of Thermal Expansion, Strain Gage Method
- 2.5.7 Dielectric Withstanding Voltage, Printed Wiring Material
- 2.6.5 Physical (Mechanical) Shock, Multilayer Printed Wiring
- 2.6.7.2 Thermal Shock-Rigid Printed Boards
- 2.6.8 Thermal Stress, Plated-Through Holes
- 2.6.9 Vibration, Rigid Printed Wiring

IPC-SM-785 Guidelines for Accelerated Reliability Testing of Surface Mount Solder Attachments

IPC-S-816 SMT Process Guideline and Checklist

1. www.ipc.org

2. Current and revised IPC Test Methods are available on the IPC website (www.ipc.org/html/testmethods.htm).

IPC-7711/21 Repair and Rework Guide**IPC-9252** Guidelines and Requirements for Electrical Testing of Unpopulated Printed Boards**IPC-9501** PWB Assembly Process Simulation for Evaluation of Electronic Components**IPC-9502** PWB Assembly Soldering Process Guidelines for Electronic Components**IPC-9504** Assembly Process Simulation for Evaluation of Non-IC Components (Preconditioning Non-IC Components)**2.2 Joint Industry Standards¹****J-STD-001** General Requirements for Soldering Electronic Interconnections**J-STD-002** Solderability Tests for Component Leads, Terminations, Lugs, Terminals and Wires**J-STD-003** Solderability Tests for Printed Boards**J-STD-020** Moisture-Induced Stress Sensitivity for Classification of Plastic Integrated Circuit Surface Mount Devices**2.3 International Tin Research Institute³****ITRI Pub #580** Metallography of Tin and Tin Alloys**ITRI Pub #708** Metallurgy of Solder Joints in Electronics**2.4 Other Publications****2.4.1 Electronic Industries Association⁴****JESD22-A104-B** "Temperature Cycling," July 2000**JESD22-B117** "BGA Ball Shear," July 2000**2.4.2 OEM Working Group⁵****SJR-01 Rev. 2** "Solder Joint Reliability Test Standard," February 2001**3 TERMS, DEFINITIONS AND CONCEPTS**

3.1 General To assure the reliability of the solder attachment of surface mounted electronic components to a circuit board substrate requires the utilization of Design for Reliability (DfR)-procedures (see IPC-D-279), **and in some cases verification by testing to qualify a product for specific**

product categories and environments. The more complex the components or the assembly, the more testing may be necessary to verify reliability.

During use, surface mount solder attachments can be subjected to a variety of loading conditions which can lead to premature failure. The underlying assumption is that the solder joints have been properly wetted, forming a good metallurgical bond between the solder and the base metal of the component build and Printed Wiring (Circuit) Board (PWB/PCB). This assures that early failures are not infant-mortalities due to defective solder joints.

The following load conditions could exist either singly, sequentially or simultaneously and combine to be large enough to cause SMT solder joint failure:

- a) 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.

The reliability of a surface mount device mounted on a circuit board is a function of solder attachment integrity and device/board interactions. Thermomechanical loading of the package, imposed by the PWB through the soldered interconnects, may cause failures in other areas of the package. The component-level testing in a socket does not provide representative part-on-board loading. The increased usage of non-wirebond die interconnects for numerous CSP constructions and high lead count BGA packages may increase the likelihood of "unexpected" internal component failures during board-level testing.

To ascertain that the solder attachment of surface mount circuit assemblies meet reliability expectations in the intended use environments, it is often necessary to confirm the reliability for some specific applications even after appropriate design for reliability (DfR) measures have been taken. Because of the time-dependent creep and stress relaxation characteristics of solder, the fatigue damage and fatigue life in accelerated testing are not generally equivalent to those in operational use, but product reliability estimates can be obtained from accelerated test results through the use of appropriate acceleration factors.

3.2 Reliability Concepts In the context of this document it is important to have a working definition of reliability, as well as good understanding of the physics-of-failure and statistical failure distribution.

3. www.itri.co.uk

4. www.eia.org

5. OEM Working Group. An informal working group of original equipment manufacturers (OEMs), Agilent Technologies, Cisco Systems, Dell, Hewlett-Packard, IBM, Lucent Technologies, Nortel Networks and Sun Microsystems.

3.2.1 Reliability Definition The ability of a product (surface mount solder attachments) to function under given conditions and for a specified period of time without exceeding acceptable failure levels.

3.3 Physics-of-Failure Concepts

3.3.1 Creep The time-dependent visco-plastic deformation as a function of applied stress and temperature.

3.3.2 Stress Relaxation The time-dependent visco-plastic deformation decreasing the stress by converting elastic strains into plastic strains for solder.

3.3.3 Solder Creep-Fatigue Model Analytical models based on empirical data that estimate the life of solder joints subjected to cyclic creep-fatigue. The estimates of reliability test results, product reliability, and the acceleration factors in this document can be determined with the Engelmaier-Wild model (see IPC-D-279, Appendix A-3.1) or some other suitable proven model.

In the Engelmaier-Wild solder fatigue model a variable fatigue ductility exponent defines the characteristic slope of the curve which correlates fatigue life with the cyclic visco-plastic strain energy experienced by the solder. This exponent is empirically determined and is a function of time and temperature in contrast to the constant exponent used for the Coffin-Manson equation, which was developed for non-creeping metals.

3.3.4 Differential Thermal Expansion The difference in thermal expansion and contractions between materials which occurs as a result of temperature changes encountered during operational use or testing for reliability. Thermal expansions or contractions are defined by the materials' coefficient of thermal expansion (CTE). Two (2) forms of differential thermal expansion are recognized:

- 1) The "global" thermal expansion mismatch, which is the thermal expansion mismatch between components and substrates.
- 2) The "local" thermal expansion mismatch, which is the thermal expansion mismatch between the solder itself and the materials to which it is bonded.

3.4 Test Parameters Note: Any definition denoted with an asterisk (*) is a reprint of the term defined in JESD22-A104-B.

3.4.1 *Working Zone The volume in the chamber in which the temperature of the load is controlled within the specified conditions.

3.4.2 Cyclic Temperature Range/Swing The difference between maximum and minimum temperatures incurred during operational use or temperature cycling tests. See Figure 3-1, Table 3-1 and Table 4-1.

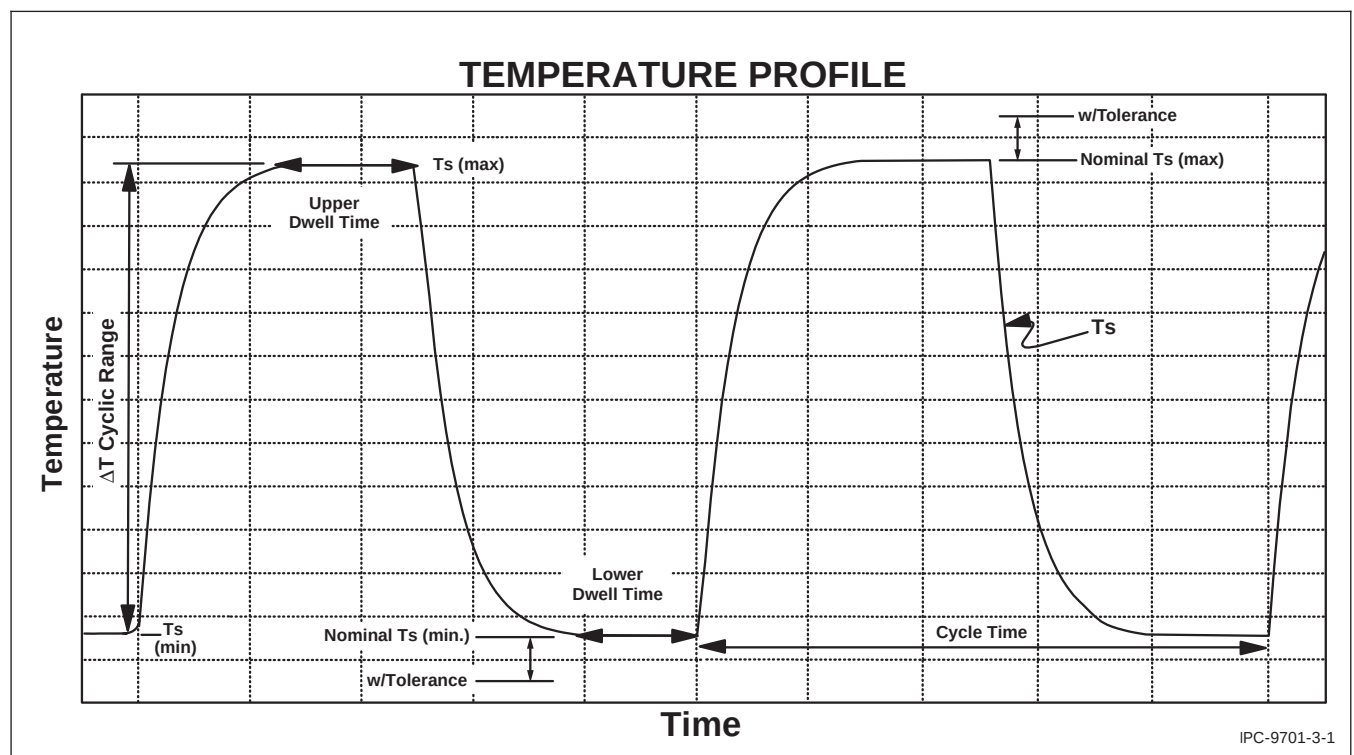


Figure 3-1 Representative Temperature Profile for Thermal Cycle Test Conditions (Figure 3-1 based upon Figure 1, Annex A of JESD22-A104-B)

Table 3-1 Product Categories and Worst-Case Use Environments for Surface Mounted Electronics (For Reference Only)

Product Category (Typical Application)	Temperature, °C / °F ⁽¹⁾		Worst-Case Use Environment						
	Storage	Operation	Tmin ⁽²⁾ °C / °F	Tmax ⁽²⁾ °C / °F	ΔT ⁽³⁾ °C / °F	t _D ⁽⁴⁾ hrs	Cycles/year	Typical years of Service	Approx. Accept. Failure Risk, %
Consumer	-40/85	0/55	0/32	60/140	35/63	12	365	1-3	1
Computers and Peripherals	-40/85	0/55	0/32	60/140	20/36	2	1460	5	0.1
Telecomm	-40/85	-40/85	-40/-40	85/185	35/63	12	365	7-20	0.01
Commercial Aircraft	-40/85	-40/85	-55/-67	95/203	20/36	12	365	20	0.001
Industrial and Automotive - Passenger Compartment	-55/150	-40/85	-55/-67	95/203	20/36 &40/72 &60/108 &80/144	12 12 12 12	185 100 60 20	10-15	0.1
Military (ground and shipboard)	-40/85	-40/85	-55/-67	95/203	40/72 &60/108	12 12	100 265	10-20	0.1
Space leo geo	-40/85	-40/85	-55/-67	95/203	3/5.4 to 100/180	1 12	8760 365	5-30	0.001
Military Aircraft a b c Maintenance	-55/125	-40/85	-55/-67	125/257	40/72 60/108 80/144	2 2 2	100 100 65	10-20	0.01
					&20/36	1	120		
Automotive (under hood)	-55/150	-40/125	-55/-67	125/257	60/108 &100/180 &140/252	1 1 2	1000 300 40	10-15	0.1

& = in addition

1. All categories may be exposed to a process temperature range of 18°C to 260°C [64.4°F to 500°F].
2. Tmin and Tmax are the operational (test) minimum and maximum temperatures, respectively, and do not determine the maximum ΔT.
3. ΔT represents the maximum temperature swing, but does not include power dissipation effects; for power dissipation calculate ΔT; power dissipation can make pure temperature cycling accelerated testing significantly inaccurate. It should be noted that the temperature range, ΔT, is not the difference between Tmin and Tmax ; ΔT is typically significantly less.
4. The dwell time, t_D, is the time available for the creep of the solder joints during each temperature half-cycle.

3.4.3 *Sample Temperature: T_s The temperature of the samples during temperature cycling, as measured by thermocouples, or equivalent temperature measurement apparatus, affixed to, or imbedded in, their bodies. The thermocouple or equivalent temperature measurement apparatus used in the attachment method should ensure that the entire mass of the sample(s) is reaching the temperature extremes and the dwell/soak requirements.

3.4.4 *Maximum Sample Temperature: $T_s(\max)$ The maximum measured temperature experienced by the sample(s).

3.4.5 Maximum Nominal Temperature: $T(\max)$ The maximum nominal temperature for a specific test condition is the required temperature $T_s(\max)$ of the sample; see Table 4-1.

3.4.6 *Minimum Sample Temperature: $T_s(\min)$ The minimum measured temperature experienced by the sample(s).

3.4.7 Minimum Nominal Temperature: $T(\min)$ The minimum nominal temperature for a specific test condition is the required temperature $T_s(\min)$ of the sample; see Table 4-1.

3.4.8 Mean Cyclic Temperature, T_{SJ} The mean of the maximum nominal temperature and the minimum nominal temperature; see Equation 4, Appendix A.

3.4.9 Nominal ΔT The difference between nominal $T(\max)$ and nominal $T(\min)$ for a specific test condition; see Table 3-1.

3.4.10 Dwell/Soak Time, t_D The total time the sample temperature is within a specified range of each nominal $T(\max)$ and $T(\min)$ (see Table 4-1). The dwell time is of particular importance for accelerated tests, since during accelerated testing the creep process is substantially incomplete. The dwell allows for a correction of the effect of the incomplete creep process relative to the product use temperature cycles which are typically long enough to allow the creep process to be complete at every cycle dwell.

3.4.11 Dwell/Soak Temperature The temperature that is above $T(\max)$ for the upper end of the cycle and is below $T(\min)$ for the lower end of the cycle. See Table 4-1.

3.4.12 Cycle Time Time for one complete temperature cycle. See Figure 3-1.

3.4.13 *Temperature Ramp Rate The rate of temperature increase or decrease per unit of time for the sample(s). The temperature ramp rate should be measured for the lin-

ear portion of the profile curve, which is generally the range between 10% and 90% of a specific test condition temperature range. Note: Ramp rate can be load dependent and should be verified for the load being tested.

3.4.14 Maximum Cyclic Strain Range The range of total strain experienced during exposure to cyclically induced thermal or mechanical deformations.

3.4.15 Maximum Cyclic Stress Range The range of total stress experienced during exposure to cyclically induced thermal or mechanical deformations. For solder in the temperature range where creep takes place, the stress range and the strain range are independent of each other (this is in contrast to noncreeping metals for which the stress-strain curve defines unique correspondences between stress and strain) since there is a different stress-strain curve for each temperature and strain-rate. The modulus and yield strength are temperature- and strain-rate-dependent, and the maximum stress experienced by the solder joints is strongly dependent on the compliancy of the attached structures, e.g., compliant leads.

3.4.16 Hysteresis Loop This loop diagrams the stress-strain behavior of solder attachments obtained during a loading cycle. The area of the hysteresis loop defines the visco-plastic strain energy per cycle, and is a measure of the fatigue damage per cycle. The size of the hysteresis loop depends on the strain range, stress range, the cyclic dwell time, and to a lesser extent on the mean cyclic temperature.

3.4.17 Design Service Life The required duration of operational life of a piece of equipment that remains fully functional while exposed to the expected environment.

3.4.18 Projected Service Life Service Life predicted by a model using accelerated test results which relates the number of fatigue cycles to a given acceptable cumulative failure probability.

3.4.19 Infant Mortality Failures Failures during environmental stress screening (ESS), burn-in, initial functional testing, and/or early in service occur primarily as a result of inadequate quality and/or manufacturing processes.

3.4.20 Random Steady-State Failures This is a period of useful operation life during which failures occur seemingly at random or at a low rate, weakly related to product complexity. For solder attachments, this period is not measurable because it may not exist or have very low failure rates.

3.4.21 Wearout Failures Wearout is defined as the process where damage accumulates over time and where the occurrences of failures rise steadily as the product deteriorates due to fatigue, or another wear-out mechanism.