

Reliability of Ceramic Column Grid Array (CCGA717) Interconnect Packages Under Extreme Temperatures for Space Applications*

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Abstract—Ceramic column grid array packages have been increasing in use based on their advantages such as high interconnect density, very good thermal and electrical performance, compatibility with standard surface-mount packaging assembly processes, and so on. CCGA packages are used in space applications such as in logic and microprocessor functions, telecommunications, flight avionics, and payload electronics. As these packages tend to have less solder joint strain relief than leaded packages, the reliability of CCGA packages is very important for short-term and long-term space missions.

CCGA interconnect electronic package printed wiring boards (PWBs) of polyimide have been assembled, inspected nondestructively, and subsequently subjected to extreme temperature thermal cycling to assess the reliability for future deep space, short- and long-term, extreme temperature missions. In this investigation, the employed temperature range covers from -185°C to $+125^{\circ}\text{C}$ extreme thermal environments. The test hardware consists of two CCGA717 packages with each package divided into four daisy-chained sections, for a total of eight daisy chains to be monitored. The CCGA717 package is $33\text{ mm} \times 33\text{ mm}$ with a 27×27 array of 80%/20% Pb/Sn columns on a 1.27 mm pitch. The resistance of daisy-chained, CCGA interconnects was continuously monitored as a function of thermal cycling. Electrical resistance measurements as a function of thermal cycling are reported and the tests to date have shown significant change in daisy chain resistance as a function of thermal cycling. The change in interconnect resistance becomes more noticeable as the number of thermal cycles increases. This paper will describe the experimental test results of CCGA testing under extreme temperatures. Standard Weibull analysis tools were used to extract the Weibull parameters to understand the CCGA failures. Optical inspection results clearly indicate that the solder joints of columns with the board and the ceramic package have failed as a function of thermal cycling. The first failure was observed at the 137th thermal cycle and 63.2% failures of daisy chains have occurred by about 664 thermal cycles. The shape parameter extracted from the Weibull plot was about 1.47, which indicates the failures were related to failures that occurred during the flat region or useful life region of the standard bathtub curve. Based on this experimental test data, one can use the CCGAs for the temperature range studied for ~ 100 thermal cycles

($\Delta T = 310^{\circ}\text{C}$, $5^{\circ}\text{C}/\text{minute}$, and 15 min dwell) with a high degree of confidence for high reliability space and other applications.

Keywords—Extreme temperatures, CCGA qualification, CCGA reliability, Weibull analysis, shape parameters, solder joint failures

INTRODUCTION

CCGA technology is an advanced electrical interconnection packaging surface mount process. This advanced CCGA interconnect technology will significantly improve the performance of high-speed systems, the productivity enhancement in manufacturing over manual wire bonding, low lead inductances, and reduced need for use of precious attachment of metals. The failure mechanisms of advanced CCGA interconnects are dependent on the materials of columns, board, the solder joints at the column/ceramic interface, column/board material interface, the solder reflow temperature, and the solder materials. The most predominant failure mechanisms are solder joint fatigue, interdiffusion, creep, and electrochemical corrosion. Any thermal coefficient expansion (TCE) mismatches between the board material and column, or between the column and the ceramic substrate causes shear displacement at each solder joint interconnect, which may lead to low-cycle thermal fatigue failure during thermal or power cycling. Reliability may be significantly increased by matching/tailoring the TCE of the substrate material, ceramic material, and the columns materials. The key contributing factors to solder joint fatigue failure are interdiffusion at the ceramic/solder and printed wiring board/solder interfaces, the solder material, dimensions of the contact area, and finally, the environment where they are going to be used. Fig. 1 shows the schematic of the 80Pb/20Sn column with copper spiral configuration in CCGA package.

LITERATURE REVIEW

CCGA packaging interconnect technology was first introduced by IBM (International Business Machines) to enhance the reliability of interconnects over ball grid array technology [1]. CCGA assembly and rework was described in depth in a user guide published by IBM [1] and elsewhere [3, 4].

CCGA permits direct electrical connection between a substrate module and a PWB. Master [2] has reported the CCGA for flip-chip applications in a temperature range of 0°C to

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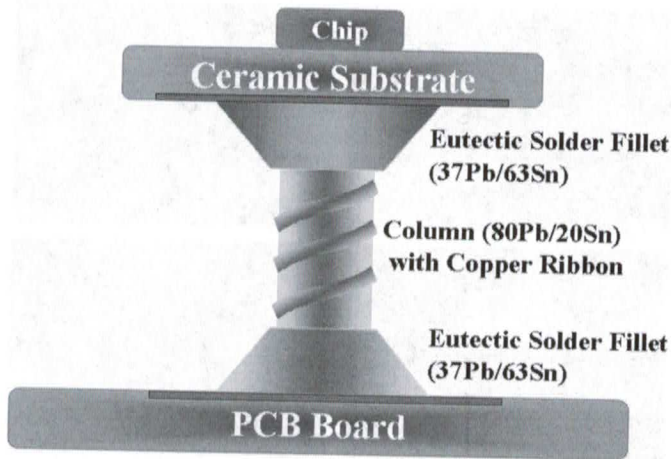


Fig. 1. Schematic of a column in a CCGA package.

+100°C and -55°C to +125°C. In this study, it was demonstrated that the column height and temperature cycling conditions were in agreement with the Coffin-Manson relationship. Aero flex (Colorado Springs, CO) has tested 472 pin CCGA daisy chained package in a temperature range of -55°C to +105°C for 500 thermal cycles and observed fractures in solder joints at board side and some also showed higher resistance [5]. Kuang and Zhao [6] have reported thermal test results of CCGA packages which meet or exceed the reliability requirements of satellite program applications. They reported reliability tests (-55°C to +105°C) for two different column material configurations such as 90Pb/10Sn (British Aerospace Engineering Systems, Manassas, VA) and 80Pb/20Sn with copper spiral from six-sigma (San Jose, CA). The results showed that the 80Pb/20Sn column material is more reliable than 90Pb/10Sn column material. The test was stopped at 2,300 thermal cycles and had no failures for 80Pb/20Sn column materials and the first failure was observed at 1,246 thermal cycles for the 90Pb/10Sn column material. One of the papers by Ghaffarian reported CCGA 717 I/O showed a minimal signs of solder joint damage at 500 thermal cycles from -55°C to +100°C and showed various levels of damage at 1,000 thermal cycles with the same temperature limits. The corner columns without staking showed a higher damage level compared with their counterparts with staking. No failures for CCGA 717 I/O assemblies after 200 thermal cycles in a range of -120°C to +85°C and also from -65°C to +150°C were seen [7-9]. Tasooji et al. [10] have reported on the design parameters influencing the reliability of CCGA assembly and a sensitivity analysis was made. Actel published and presented some of the CCGA data for reliability for space applications [11, 12]. Lau and Dauksher have reported 1657 CCGA with lead free solder data [13].

Titan (-180°C, for a proposed Titan in-situ mission), Europa (-160°C, for a proposed Europa surface and subsurface mission), asteroids (-185°C, MUSES-CN project), comets (-140°C, for a proposed comet nucleus sample return), Earth's moon (recorded temperature on the moon: -233°C to +123°C, moon mineralogy and mapper, M³), and Mars [MER (-120°C to +85°C), MSL (-143°C to +85°C)] require operations of thermally uncontrolled hardware under extremely cold temperatures and hot temperatures with a large diurnal temperature

Table I
Prior and Present Research Work and the Temperature Used in the Respective Studies to Assess the Reliability of CCGA Packaging Technology over a Wide Temperature Range

Authors	[Ref.]	Temperature range (°C)
Ramesham	This work	-185 to 125 0 to 100
Master	[2]	-55 to 125
Aeroflex	[5]	-55 to 100
Khuang and Zhao	[6]	-55 to 105 -55 to 100
Ghaffarian	[7-9]	-120 to 85
Mehta and Bodie	[3, 4]	-55 to 100

change from day to night. Planetary protection requires the hardware to be baked at +125°C for 72 h to kill microorganisms to avoid any biological contamination, especially for sample return missions. NASA standards thermal cycling temperature range varies from -55°C to +100°C per NHB-5300.4 (3A-1) (NASA Handbook: Requirements for soldered electrical connections, Dec 1976). Therefore, the present CCGA package reliability research study has encompassed the temperature range of -185°C to +125°C to cover various potential future NASA deep space missions.

Based on the existing published data, to the best of author's knowledge there is no published systematic experimental data available to assess the reliability of CCGA packages in extremely cold and hot temperatures such as -185°C to +125°C. Therefore, this paper describes the important experimental test results obtained in this extreme temperature range. Table I provides the summary of the literature review of prior and present research study of CCGA reliability over a wide temperature range.

WEIBULL DISTRIBUTION

The Weibull distribution is widely used in reliability and life data analysis due to its versatility. The Weibull distribution can be used to model a variety of solder joint life behaviors depending on the values of the parameters. The values of the shape parameter (β), the scale parameter (η), and the location parameter (μ) affect such distribution characteristics as the shape of the probability distribution function (pdf) curve, the reliability, and the failure rate. Many probability distributions are not a single distribution, but are in fact a family of distributions. This is due to the distribution having one or more shape parameters. Shape parameters allow a distribution to take on a variety of shapes, depending on the value of the shape parameter. Plots of the Weibull probability distribution function with the values for the shape parameter of 0.5, 1.0, 2.0, and 5.0 include an exponential distribution, a right-skewed distribution, and a relatively symmetric distribution. The Weibull plot has special scales that are designed so that if the data do in fact follow a Weibull distribution, the points will be linear (or nearly linear). The least squares fit of this line yields estimates for the shape and scale parameters of the Weibull distribution [14, 15]. The most general expression of the Weibull pdf is given by the three-parameter Weibull distribution expression, or:

$$f(T) = \beta/\eta[(T-\gamma)/\eta]^{\beta-1} e^{-[(T-\gamma)/\eta]^\beta}$$

where

$$f(T) \geq 0, T \geq 0 \text{ or } \gamma, \beta > 0, \eta > 0, -\infty < \gamma < \infty$$

and

- β is the shape parameter, also known as the Weibull slope
- η is the scale parameter
- γ is the location parameter

WEIBULL SLOPE OR WEIBULL SHAPE PARAMETER, β

The Weibull shape parameter (β) is also known as the Weibull slope. This is because the value of β is equal to the slope of the line in a probability plot. Different values of the shape parameter can have marked effects on the behavior of the distribution as described above. This is one of the most important aspects of the effect of β on the Weibull distribution. As is indicated by the plot, Weibull distributions with $\beta < 1$ have a failure rate that decreases with time, also known as infant mortality failures or early-life failures. Weibull distributions with β close to or equal to 1 have a fairly constant failure rate, indicative of useful life or random failures. Weibull distributions with $\beta > 1$ have a failure rate that increases with time, also known as wear-out failures. These are the three sections of the classic “bathtub curve” [14, 15].

FABRICATION OF TEST BOARDS

The boards were manufactured using a process reported by Mehta and Bodie [3, 4]. They used the developed processes to qualify CCGA package assemblies using printed wiring board daisy chain CCGA packages. Fig. 2 shows the optical photographs of the as received CCGA packages prior to reflow at various magnifications. A complete CCGA array package is also shown in Fig. 2 (33 mm \times 33 mm). The copper spiral can be seen around the column interconnect material. The use of the copper spiral around the column materials would tend to increase the integrity of the column interconnect during the solder reflow process. Figs. 3(a) and 3(b) show digital photographs of the CCGA packages after reflow over the PWB. The complete CCGA package may be seen in Fig. 3(a), along with highly magnified views of the columns and also the copper spiral around the column material. Fig. 4 shows the non-destructive x-ray images of the CCGA packages after solder reflow. There were no shorts or overflow of solder materials that can affect the CCGA packages and their reliability. X-ray images also confirmed there were no shorts.

A. Temperature Profile

Fig. 5 shows the thermal cycling temperature profile employed in this experimental study to perform the cycling of the daisy chained CCGA interconnect test boards. The lowest temperature was -185°C and the highest temperature used was $+125^\circ\text{C}$. The temperature ramp rate was $5^\circ\text{C}/\text{min}$ and the dwell time was 15 min for both hot and cold temperatures during thermal cycling.

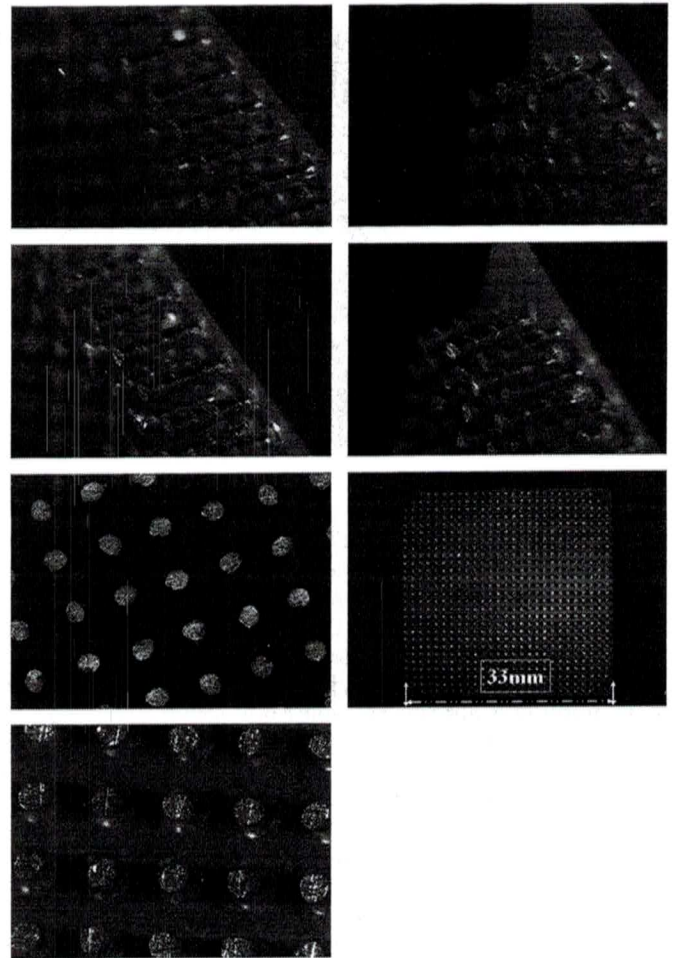
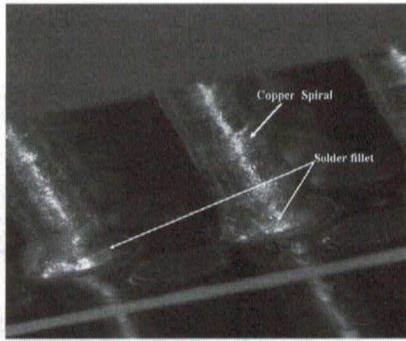
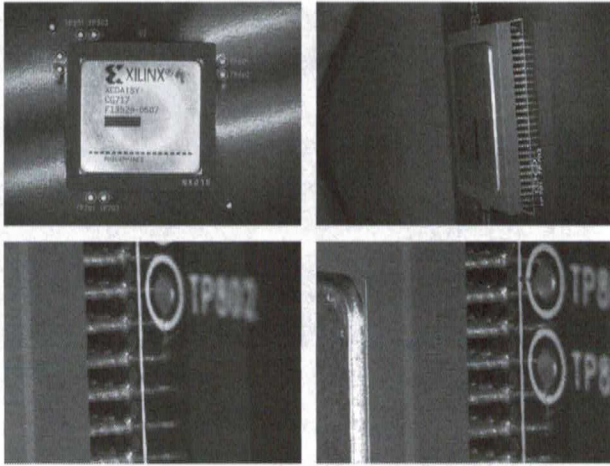


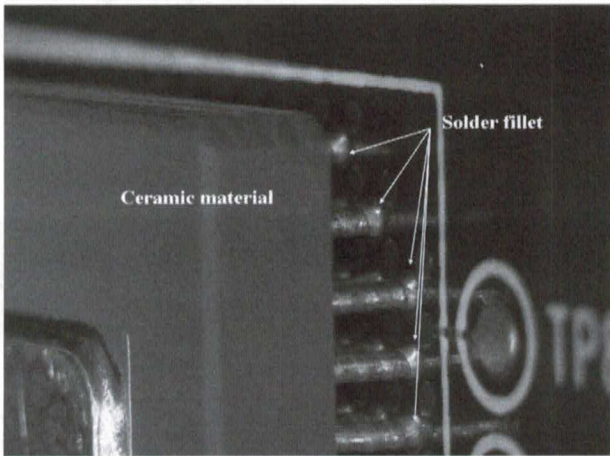
Fig. 2. As-received test CCGA packages.

B. Testing for Overstress Interconnect Fracture and Intermittent Failures

There were four daisy chains on board for each CCGA daisy chain package. The value of the daisy chain resistance was about $\sim 2 \Omega$ at room temperature. A test was conducted to assess the advanced CCGA interconnect technology based on the possible failure mechanisms. The key failure mechanism addressed in thermal cycling is solder joint fracture, generally found either at the board and column interface or at the column and ceramic package substrate surface. Temperature cycling may result in thermal fatigue of the solder joint and interdiffusion at the substrate/column or column and ceramic substrate interface. The stress depends on the magnitude of the temperature either on the high temperature side or low temperature side, the rate of temperature change, and range (ΔT) of temperature, and also CTE of the materials combination involved in this configuration. A high rate of change of temperature (i.e., change in temperature per minute) could lead to thermal shock of the advanced CCGA interconnect packages which could have a catastrophic effect on the reliability of the solder joints. Therefore, a low rate of change of temperature ($5^\circ\text{C}/\text{min}$) has been employed in this experimental study. Fig. 6 shows the daisy chain resistance as a function of



(a)



(b)

Fig. 3. (a) CCGA column after reflow. (b) Solder fillets of CCGA column.

temperature. Resistance of the solder joint increases as the temperature increases and decreases as the temperature decreases. The first solder joint failure was observed at the 137th thermal cycle. The resistance of one of the daisy chain increased beyond 3.5Ω and also beyond 100Ω as shown in Figs. 7 and 8. Fig. 8 shows the resistance of solder joints as a function of thermal cycles. An increase in the resistance of the daisy chain to 1000Ω certainly provides reason to conclude that the daisy chain has failed. Figs. 9 and 10 show the intermittent change in resistance to a higher value when the test article reached hot and cold temperatures for different daisy

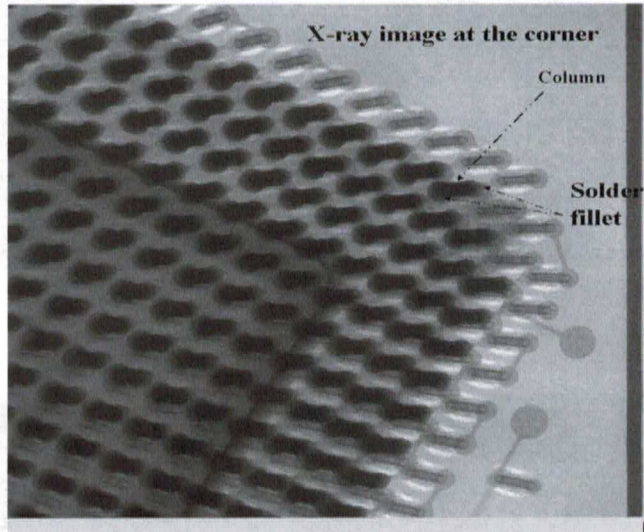
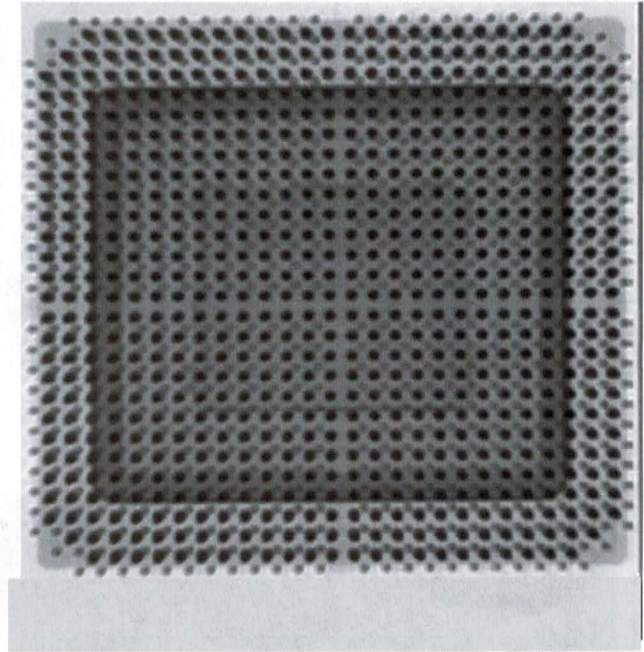


Fig. 4. X-ray images of the reflowed packages.

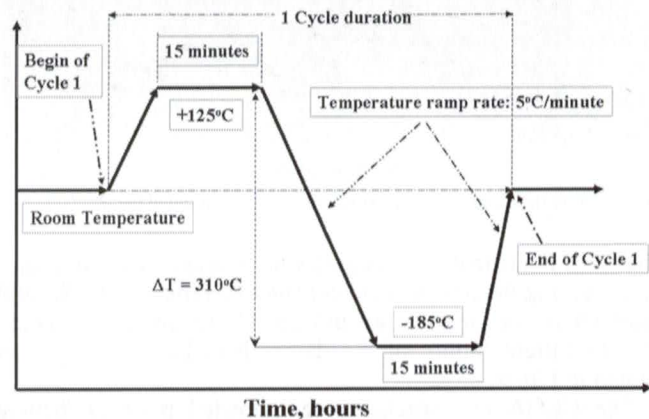


Fig. 5. Extreme temperature thermal cycling profile using in this study.

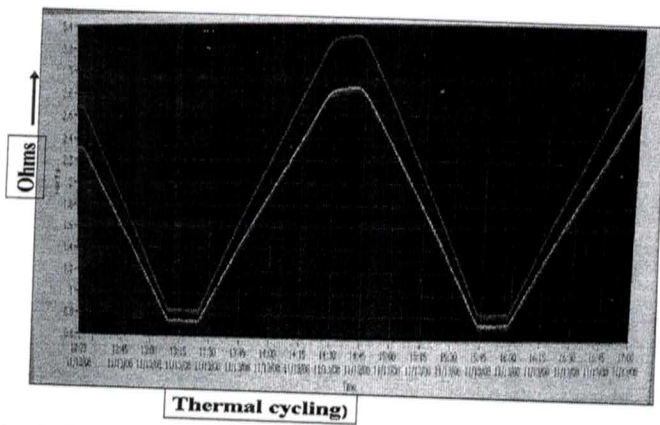


Fig. 6. Resistance of daisy chains versus thermal cycling duration.

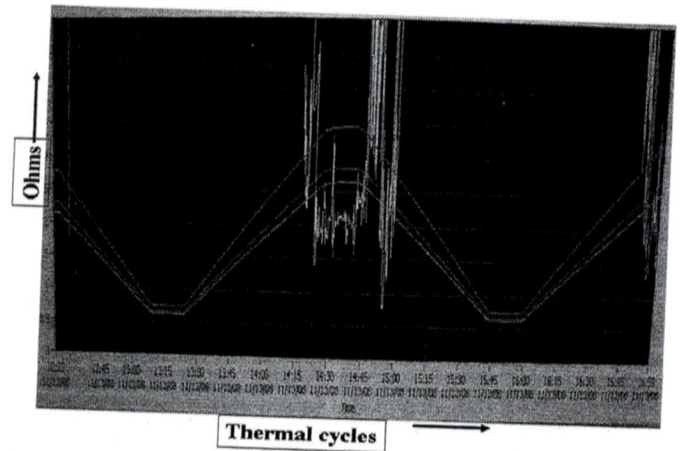


Fig. 9. Intermittent failure of solder joints.

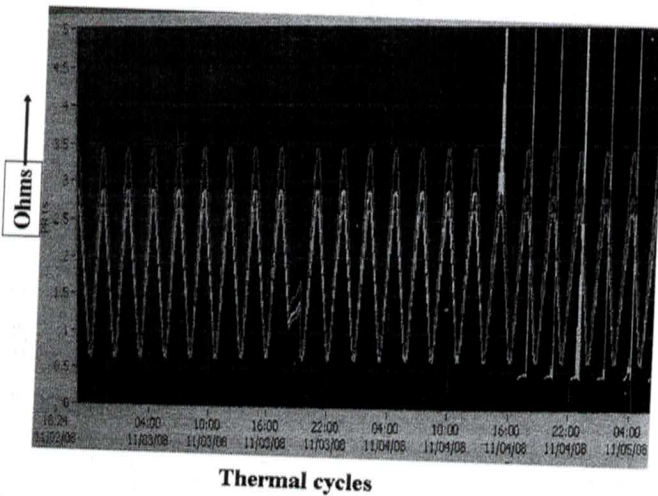


Fig. 7. Failure of daisy chains during thermal cycling.

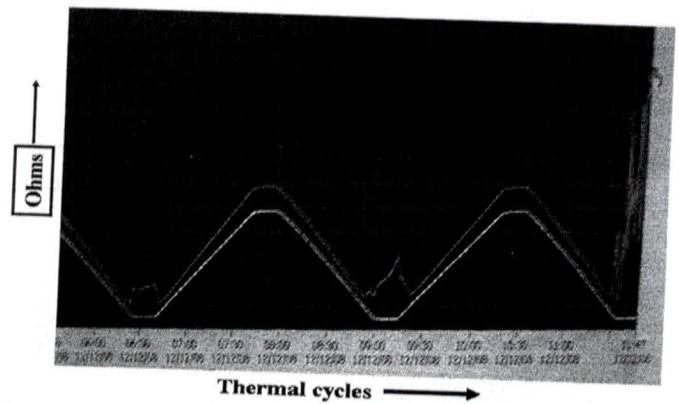


Fig. 10. Initiation of intermittent failures during thermal cycling.

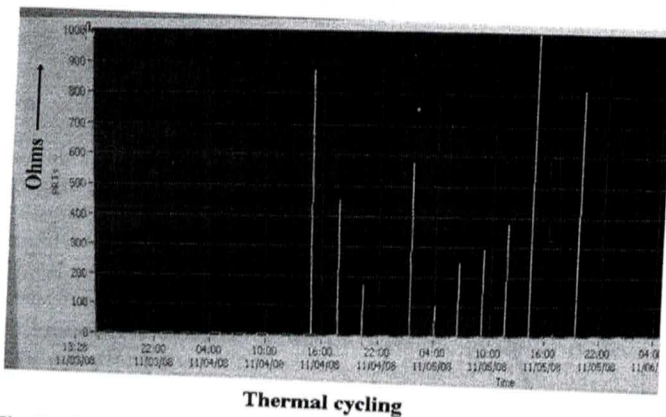


Fig. 8. Resistance of daisy chains has increased to about 1000 Ω .

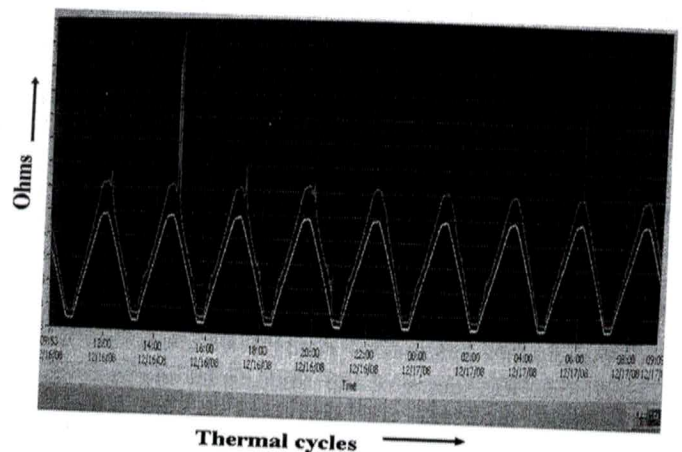


Fig. 11. Intermittent failure of solder joint during thermal cycling.

chains. It is difficult to conclude what caused the daisy chains to fail during the hot and cold portion of thermal cycle. Several daisy chains failed as shown in Figs. 11, 12, and 13. Initiation of intermittent failure of the daisy chain has just begun as shown in Fig. 9.

The CCGA test articles were inspected prior to thermal cycling and later subjected to thermal cycling. The CCGA pack-

ages were inspected after 1,058 thermal cycles. However, the daisy chains were monitored continuously during thermal cycling from the beginning of the test. Failures were observed in CCGA testing under extreme temperature thermal cycling. The first failure was observed in the test article at the 137th

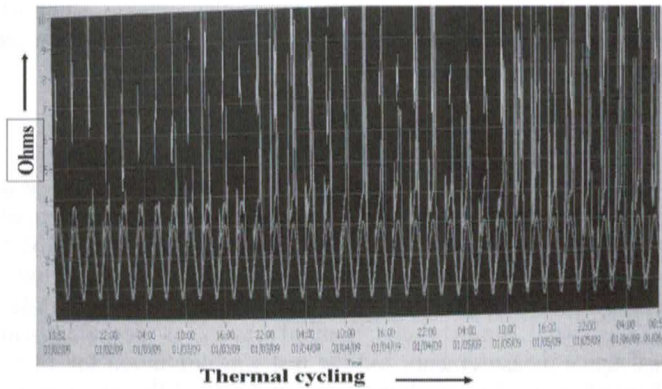


Fig. 12. Several failed daisy chains during thermal cycling.

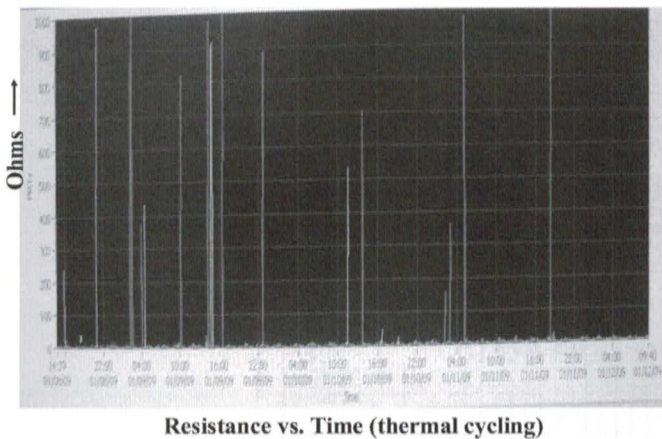


Fig. 13. Several daisy chains with open circuits after thermal cycling.

thermal cycle performed from -185°C to $+125^{\circ}\text{C}$. This failure is an intermittent failure which is reproducible for the subsequent thermal cycles tested. There were six failures during the complete thermal cycling test. The ΔT of this test was 310°C , which is significantly higher than for military applications (-65°C to 125°C) and NASA thermal cycles ($\Delta T = 155^{\circ}\text{C}$, temperature range: -55°C to 100°C). The CCGA solder joint showed a closed circuit when the board was at high temperature and an open circuit when the board was at low temperature. Fig. 14 shows optical photographs of the CCGAs that were inspected after 1,058 thermal cycles. Several micrographs show significant damage of solder joints particularly at the corners of the package. Some of the columns have been dislodged from their original solder joint position. Several cracks in the solder joints were observed. The failures occurred at the column and board interface and also at the column and ceramic interface. Figs. 15 and 16 show a higher magnification of the failed solder joints. Fig. 16 shows the clear dislodging of the column interconnects from their original position, especially at the corners of the package. Fig. 17 shows a digital photograph of the complete CCGA package after 1,058 thermal cycles.

C. Reliability Analysis

Reliability of CCGAs decreases as a function of thermal cycles. Fig. 18 shows reliability versus thermal cycles to

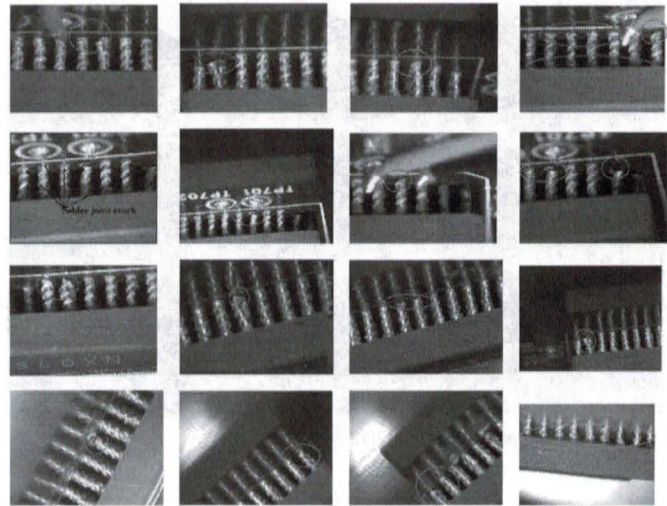


Fig. 14. CCGAs after 1,058 thermal cycles -185°C to 125°C .

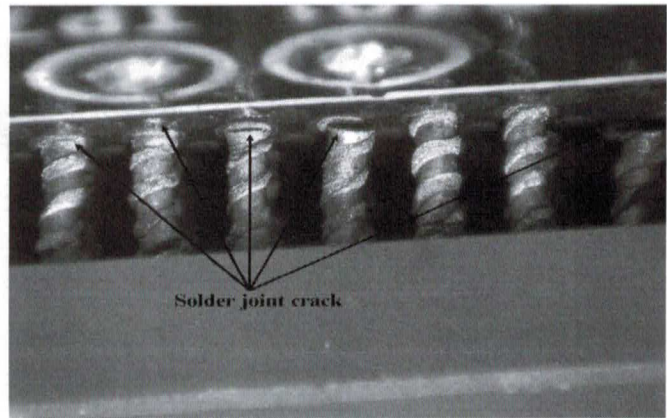


Fig. 15. Failed solder joint.

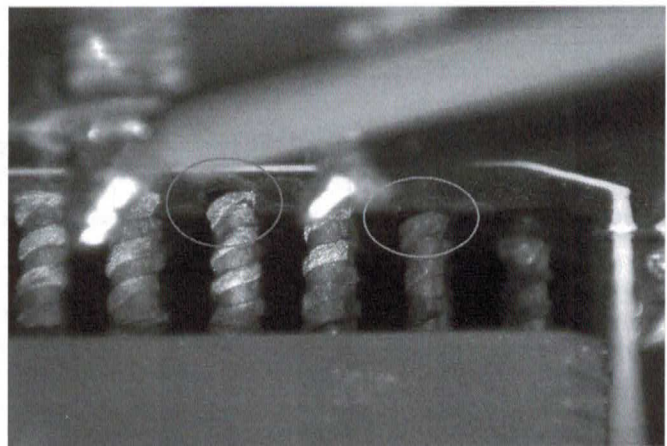


Fig. 16. Dislodged column at the corner of a CCGA package after thermal cycling.

failure. It may be inferred from Fig. 18 that the reliability is 90% for around 140 thermal cycles from -185°C to 125°C . Fig. 19 shows the unreliability versus thermal cycles to failure data. The Weibull shape factor/parameter is about 1.47,

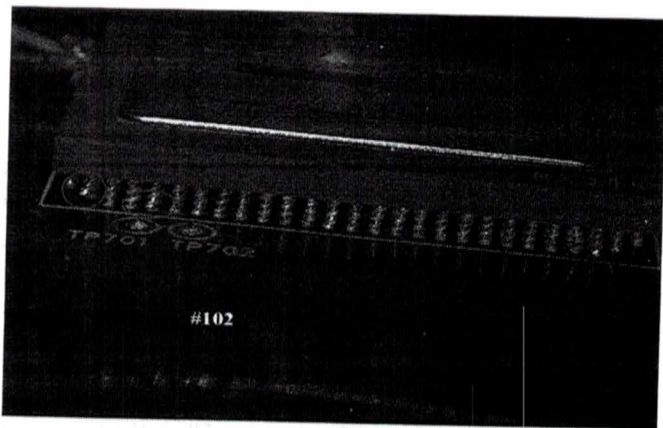


Fig. 17. CCGA package after 1,058 thermal cycles.

which indicates the failures are within the useable range of bathtub curve. This also follows the Raleigh distribution as provided in Fig. 20 [14, 15].

CONCLUSIONS

Advanced CCGA packaging interconnect technology test objects have been subjected to extreme temperature thermal cycles. The change in resistance of the daisy chained CCGA interconnects was measured as a function of number of thermal cycles. Several catastrophic failures were observed after 137 extreme temperatures thermal cycles as per electrical resistance measurements and the test was continued for 1,058 thermal cycles to corroborate and understand the test results. Process qualification and assembly is required to optimize the CCGA assembly, which is very clear from the x-ray. X-ray

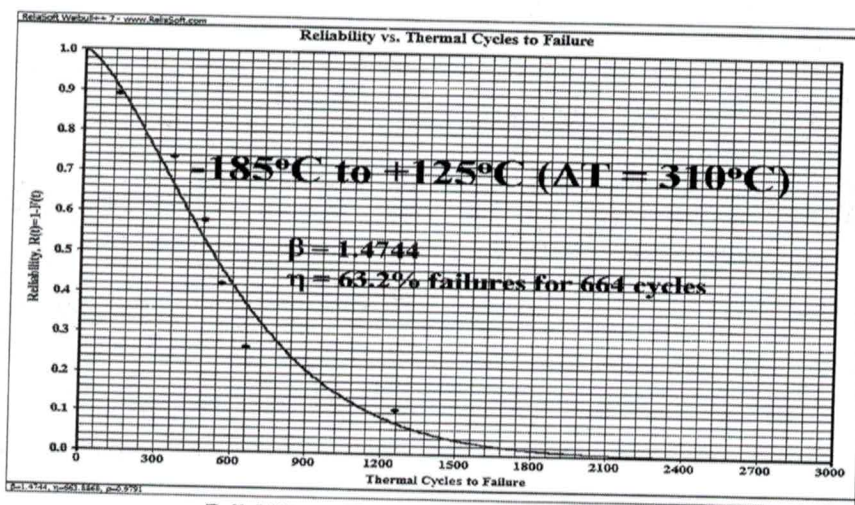


Fig. 18. Reliability versus thermal cycles to failure data generated using experimental test.

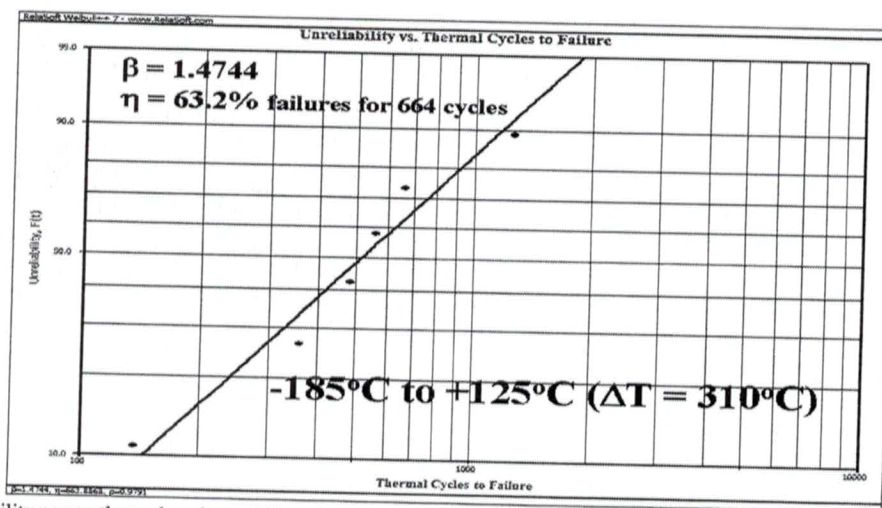
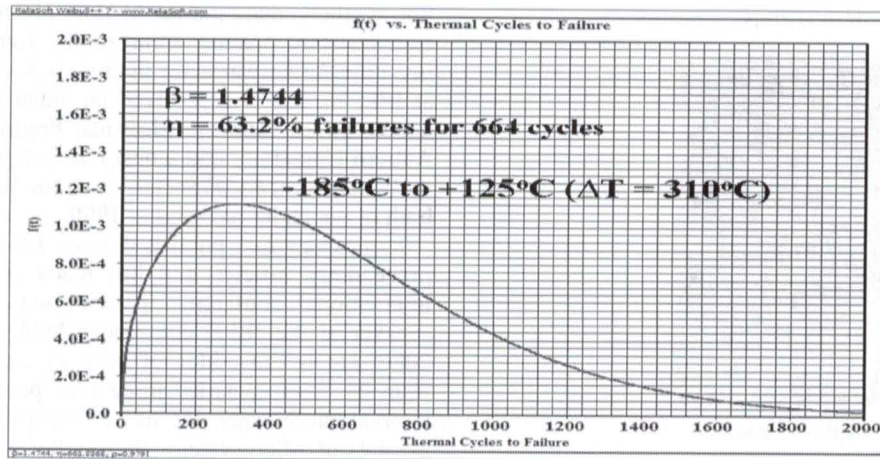


Fig. 19. A plot of unreliability versus thermal cycles to failure data generated using experimental test data.



Probabilistic Distribution Function Plot

Fig. 20. Probabilistic distribution function plot generated using the experimental test data.

and optical inspection were done after thermal cycling. Failures were observed based on electrical resistance measurements during extreme temperature thermal cycling after 137 thermal cycles. Six daisy chains were open out of eight daisy chains as per the experimental test data reported. Daisy chains are open during the cold cycle and recover during the hot cycle.

- CCGA packages have been tested from -185°C to 125°C for 1,258 thermal cycles.
- 63.2% failures were observed for ~ 664 thermal cycles. Thermal cycles were defined as the time at which 63.2% of the device population would have failed.
- A shape factor of more than 1 indicates that this is related to constant failure rate during normal life or useful life of the package in a bathtub curve.
- The first failure was observed at 137 thermal cycles for a ΔT of 310°C .
- Extrapolation of this data to lower ΔT conditions could qualitatively provide insight into their use for longer duration applications using Coffin-Manson relationship.
- The corner columns were the first to fail or be dislodged. Two failure mechanisms were realized: (1) dislodging the column from the board/ceramic, and (2) failure of solder fillets and other failure mechanisms which have not yet been explored.
- Solder was dislodged from the pad as can be seen in digital photographs.
- Optical (conclusive) and x-ray imaging inspections were used to inspect the CCGA versus thermal cycles. The x-ray images were not that conclusive.

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BIOGRAPHY



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Dr. Rajeshuni Ramesham joined JPL in 1997 and presently is a Principal Member of Engineering Staff. At the academic level, he has worked on the research faculty at Auburn University, Auburn, Alabama from 1989-1997. He was an adjunct professor at Auburn University, Auburn, AL. His present research work at JPL is focused on extreme temperature electronics and interconnects reliability, the reliability of packaging and interconnects associated with the MEMS/MOEMS for space applications. Ram currently has devoted most of his time toward the JPL/NASA Mars Science Laboratory, JUNO, and GRAIL projects. He worked on the application of polycrystal-

line synthetic diamond for MEMS, electrochemical and corrosion resistant coating applications. Ram is the recipient of several NASA awards for the research work he has performed at JPL. He has also received an outstanding research performance award from the Electrical Engineering Department of Auburn University and a best research paper award published in *J. Electrochemical Society* from the IEEE Alabama Section; both of which he received in 1990.

Ramesham has published over 125 refereed journal and proceedings articles and has made over 100 national and international conference presentations. He was a Keynote speaker at the IEEE conference held in Las Vegas in May 2000. He is the editor of over 12 conference proceedings. Ram has been awarded three U.S. patents and seven NASA internal disclosures. He has published a chapter in "Fundamentals of Microsystems Packaging" published by McGraw-Hill. Ramesham has been a conference chair, workshop general chair, and technical chair for various MEMS, MOEMS, E-Nose, optoelectronics packaging, and low temperature electronics sponsored by various societies. He served as Symposium Chair for MOEMS-MEMS Micro & Nanofabrication Symposium, a part of Photonics West. He is presently serving as a member of the Steering Committee for MOEMS/MEMS symposium and also as a conference Chair for Reliability, Packaging, Testing, and Characterization of MEMS/MOEMS. He organized thermal testing panel discussions at TFAWS-2008 and ICES-2009 addressing for NASA's and other space agencies' applications.