Assembly Reliability of CSPs with Various Chip Sizes by Accelerated Thermal and Mechanical Cycling Test

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ABSTRACT

A JPL-led chip scale package (CSP) Consortium, composed of team members representing government agencies and private companies, recently joined together to pool in-kind resources for developing the quality and reliability of chip scale packages (CSPs) for a variety of projects.

The experience of the Consortium in building more than 150 test vehicle assemblies, single- and double-sided multilayer PWBs, and the environmental test results has now been published as a chip scale packaging guidelines document and distributed by Interconnection Technology Research Institute (ITRI).

The Consortium assembled fifteen different packages from 48 to 784 I/Os and pitches from 0.5 to 1.27 mm on multilayer FR-4 printed wiring board (PWB). In addition, two other test vehicles built by two team members, each had a control wafer level CSP package for data comparison. Assemblies were subjected to numerous thermal cycling conditions including -55°C to 125°C. Thermal cycles-to-failure (TCTF) test results to 900 cycles for a grid CSP with 0.8 mm pitch, package area of 16 by 16 mm, and die sizes of 7.3, 9.5, and 11.8 mm are compared. Mechanical cycles-to-failures (MCTFs) test results under deflections in the range of 0.125 mm to 1.875 mm (0.005" to 0.075 inches) for the same package assemblies under three point mechanical fatigue were determined and presented. Reduction in MCTFs due heat generated by application of current into package/PWB daisy chain resistance were also presented.

INTRODUCTION

Chip Scale Packages (CSP) are now widely used for many electronic applications including portable and telecommunication products. The CSP definition has evolved as the technology has matured and refer to those packages with a pitch of 0.8 mm and lower. Packages with fine pitches especially those with less than 0.8 mm and higher I/Os may require the use of microvia printed wiring board (PWB) which is costly and they may perform poorly when are assembled on board. A test vehicle (TV-1) with eleven package types and pitches was built and tested by the JPL MicrotypeBGA Consortium during 1997 to 1999. Lessons learned by the team were published as a guidelines document for industry use[1].

The finer pitch CSP packages which recently become available were included in the next test vehicle of the JPL CSP Consortium[2]. The Consortium team jointly concentrated their efforts on building of the second test vehicle (TV-2) with fifteen (15) packages of low to high I/O counts (48 to 784) and pitches of 0.5 mm to 1.27 mm. In addition to the TV-2 test vehicle, other test vehicles were designed and built by individual team members to meet their needs. At least one common package was included as control in each of these test vehicles in order to be able to compare the environmental test results and understand the effects of PWB build and manufacturing variables.

One test vehicle was designed and assembled by Hughes Network System using their internal resources and is identified as TV-H. In this paper the most recent thermal cycling test results to 900 cycles currently being performed under -55 to 125°C for packages with various die sizes are presented. Mechanical fatigue test results for the 280 I/O count packages under various deflections with and without local heating were also presented.

CSP TEST MATRIX

Test Vehicle Package I/O /PWB

The TV-H had eight packages ranging from 48 to 280 I/Os with pitches of 0.8 mm as shown in Figure 1 The PWB had four layers with the two RCC layers and an FR-4 core (1+2+1) having a total thickness of 0.43 mm. Microvia technology was used. The pad had a 0.1 mm (4 mil) microvia hole at the center of pad. A non-solder-mask-design (NSMD) pad with the diameter of 0.3 mm and 0.05 mm clearance was used. The surface finish of PWB was Ni/Au immersion with about 2-8 micro inch of gold over 100-200 micro inch Ni. No clean solder paste for assembly was applied with a 5 mm thickness laser cut stencil. The test vehicle was 4.75" by 1.85" with one connector attached for continuous thermal cycling monitoring. The width of test vehicle was cut into 1" for the three point bend fatigue testing.

280 I/O Package/Test Vehicle Features

Figure 1 shows a full populated test vehicle (TV-H) with two sites for the 280 I/O fine pitch ball grid array, U4 and U2 sites. All packages were daisy-chained, and they were divided into several internal chain patterns. The daisy chain pattern on PWB complete the chain loop into the package through solder joints. Several probing pads connected to daisy chain loops were added for failure site diagnostic testing. The package and PWB daisy chains for the 280 I/O package is shown at the bottom of Figures 2. All locations sites including U4 and U2 sites were populated for the thermal cycling assembly testing. Only the U4 location was populated for mechanical cycling testing. All packages were prebaked at 125°C for 2 ½ hours prior to assembly.

TEST CONDITIONS

Thermal Cycling test

Thermal cycling was performed in the range of –55°C to 125°C. Chamber setting and thermal couple readings are shown in Figure 3. The heating and cooling rates were 2° to 5°C/min with a dwell at maximum temperature of more than 10 minutes and a shorter dwell time duration at the minimum temperature. Each cycle lasted 159 minutes.

The test vehicles were monitored continuously during the thermal cycles for electrical interruptions and opens. The criteria for an open solder joint specified in IPC-SM-785, Sect. 7.8, were used as guidelines to interpret electrical interruptions. Generally, once the first interruption was observed, there were many additional interruptions within 10% of the cycle life. In addition, daisy chain opens were verified manually at room temperature after weekly removal of the test vehicles with failed assemblies from the chamber.

Mechanical Cycling Test

Mechanical cycling test was performed using a three point bending test set up as shown schematically in Figure 2. This test vehicle coupon had one package at its center which the center of package along the PWB was set on stationary ram of the fixture with 0.125 mm (1/8) radius. The coupon was in contact along its edges with two moving bars, spacing at 80 mm with 3.13 mm (1/8 inch) radius. These two bars pushed the coupons down into the stationary ram with specified maximum deflections for mechanical cycling. To determine the maximum deflection of assembly under static condition, a test coupon was tested to failure by continuously increasing deflection. Failure was automatically detected by application of current to daisy chain with 3.2 ohms to achieve a four (4) volts output. Monitoring was accomplished by interfacing a PC into the output signal from the mechanical testing system and recording data. When daisy chain become open, the output voltage from the system increased to 4.16 volts. Voltage output and deflection levels were continuously recorded in a data base for retrieval and data analysis.

The first three test results were inconsistent and they failed at unexpectedly very low values. Two observations were made: (1) the test coupon was slightly moved during it zero deflection state, and (2) the application of high current into daisy chain introduced heat in the package. The first observation was corrected by using a double sided tape to the bars in order to minimize the movement of coupon. The second observation allowed to use current for a set of test coupons and thereby further accelerated cycles-to-failure relative to a no-current condition. To know the effects of current on package temperature, the package surface temperature was monitored by thermal couple before the start and during mechanical cycling. The temperature rises were in the range of 95°C-105°C. When no current was applied, the daisy chain resistance was monitored visually using a multimeter. The first increase in resistance considered initiation of failure and was reported. Test was continued till complete daisy chain open and this value was also recorded.

TEST RESULTS

Only a limited number of test vehicles were subjected to accelerated thermal cycling condition (-55 to 125°C). The most recent thermal cycle test results to 900 cycles for these are presented here. Cycles-to-failure (CTF) results for the 280 I/O package with 3 die sizes are compared and discussed. Preliminary test results for several other packages presented elsewhere[2]. CTF for other packages and under other thermal conditions are being gathered and will be analyzed and presented in the future.

Twenty test coupons were used for accelerated mechanical cycling testing under deflection levels from 0.125 mm to 1.875 mm (0.005" to 0.075"). The maximum cycling deflection value represents approximately 30% of maximum deflection under static test. MCTF for assemblies with various die sizes for single and combination of two to three deflection levels to 300,000 cycles were presented. The effects of local thermal heating on MCTF degradation were also determined and presented. Degradation due to assembly exposure at high temperature representative of curing of an underfill was also presented.

Thermal Cycling Results

Figure 4 shows cycles to first failures for the 280 I/O FPBGA with 3 die sizes. It also includes the CTFs for the 208 I/O package with 11.4 mm die with an identical package technology. To generate plots, the CTFs were ranked from low to high and failure distribution percentiles were approximated using median plotting position, $F_i = (i-0.3)/(n+0.4)$. For this package technology, the relative die size had the most significant affect on CTF. The 208 I/O package with an 11.4 mm die size in a 15 mm package showed CTF in the range of 176 to 573 cycles. The 280 I/O package with an 11.8 mm die in 16 mm packages failed in the range of 303 to 824 cycles. CTFs for assemblies at the center of PWB (U4 site) and the edge were also distinguished marked by square and triangle. Even though most of U4 packages failed a higher cycles, it is not clear if they are due to location of package on PWB or manufacturing anomaly. Only two out of 10 assemblies with 9.5 mm die failed at 690 and 836 cycles.

Mechanical Cycling Results

Mechanical cycling test results under different conditions are summarized and listed in Table 1. Conditions were failure under static deflection and failure under mechanical cycling without and with application of 4 volts to package/PWB daisy chain resistance (3.2 Ohms). The load deflection under static condition was determined and found to have a linear relationship, i.e. as load increased the deflection increased. The maximum deflection prior to failure was 5.65 mm (0.226") under 4 volt condition. This value is expected to be higher if no current were applied to daisy chain during testing.

To achieve acceleration failure to less than a day under 5 Hz cycling frequency (10,000 cycles for every 33 minutes), damage levels were accumulated under increasing level of deflections. Deflection levels were increased when assemblies survived 10,000 cycles under one level of deflection. Further acceleration was achieved by application of current to daisy chain resistance of package/PWB. Data presented in Table 1 clearly indicate that assemblies failed under maximum combined deflection of 1.25 mm (.050") for 4 volt condition. The maximum deflection increased to 1.875 mm (.075") when no current applied. If no damage accumulation technique is used then assemblies under deflection of .625 mm (0.025") with and without current failed at 104,000 and more than 300,000 cycles, respectively. Note MCTF reduction when assemblies were subjected to 150°C for only 20 minutes. This temperature and time represent cure of a reworkable underfill.

Failure Mechanisms

Assemblies are currently being subjected to scanning electron microscopy, cross-sectioning, and pull test to determine failure mechanisms due various accelerated mechanical cycling. However several observations were made during mechanical cycling when assemblies start to show signs of failure. One aspect was included in the Table by listing the MCTF range from the start of daisy chain voltage/Ohm increase to complete daisy chain open. In general increase in resistance or voltage was slow and sometimes it required to have thousands of additional cycles before complete daisy chain open under loading (deflection). Failure under load was not permanent for most cases, especially for no voltage condition. Daisy chain showed increase in resistance after removal of load, but not complete open. Under current application condition, sometimes complete failure occurred under both load and no load condition.

DISCUSSION

New applications of advanced electronic packaging including chip scale package in consumer portable products brought about new environmental requirements not seen in their previous generation of relatively benign office applications. The on/off cycles introduce failure of solder joints due to thermal mismatch of package and PWB. Solder joint integrity is critical since it carry both mechanical and electrical load. Failure of solder joint due to CTE mismatch has commonly characterized using a dummy package daisy chained through solder and PWB by monitoring their failure under temperature cycling. Use of power cycling, i.e. heat locally solder by imbedding resistance inside of the package, now are being considered as alternative since it provides higher reliability results much needed for miniature packages.

In addition to on/off cycles, electronics in portable products are required also to be robust under mechanical conditions, e.g. robustness to repeated mechanical cycling due to key punching and to shock due to drop or bending due to sit on product. The mechanical requirement are not new for high reliability application environments including automotive, military, and aerospace. Conventional leaded SMT packages have shown to be robust. Unfortunately, both the use of rigid balls instead of flexible lead and reduction of interconnect area for most CSPs due to reduction in package size have negative effects on their environmental robustness. Accelerated thermal and mechanical testing are required to screen for different design and also to determine robustness of CSPs in order to meet the increasing demand for time to market shrinkage for consumer products and effective use of these products for high reliability applications.

Mechanical cycling tests, if they provide the same trends as thermal cycling, could be very effective accelerated technique. The investigation performed here was aimed at characterizing behavior of CSPs under mechanical condition and to determine if techniques can be developed to determine trends that are being established under thermal cycling conditions. One key parameter that affects thermal cycles to failure is the die size in a CSP. Thermal cycling of package with various die sizes clearly indicated the criticality of die size and their effects on solder joint reliability. With limited test performed, it appears that there is possibility that such trend can be established by mechanical cycling.

Mechanical tests with no local package heating will significantly overestimate the life of solder joint. Local heating will accelerated life testing and provide a better representative of application. A very promising accelerated test results under mechanical cycling was for those assemblies exposed to isothermal aging at 150°C for 20 minutes. These assemblies clearly showed much lower mechanical cycles to failure and the trend was apparent. Further works are required to be performed to determine that if this accelerated technique could be used to screen for variety of manufacturing defect and possibly in conjunction with limited thermal testing to project life for intended applications.

CONCLUSIONS

These conclusions are based on results limited to assembly failure to 900 thermal cycles in the range of -55°C to 125°C and limited number of mechanical cycling test to failure.

- Cycles-to-failures for the fine pitch ball grid array (FPBGA) with 0.8 mm pitch were in the ranged of 300 to 800 cycles. These are significantly much lower than their BGA counterparts with 1.27 mm.
- Cycles-to-failure decreased as package die size decreased. The 208 I/O FPBGA package with the largest relative die size to package dimension (11.4 mm die in 15 mm package) showed the lowest cycles to failure, followed by the 280 I/O package with a slightly smaller relative die size to package (11.8 in 16 mm). The effects of die sizes were as follows:
  - Eight out of eight (8/8)of the 208 I/O assemblies with 11.4 mm die failed in the range of 176 to 573 cycles
  - Fourteen out of fourteen (14/14) of the 280 I/O assemblies with 11.8 mm die failed in the range of 303 to 824 cycles
  - Two out of 10 (2/10) of the 280 I/O assemblies with 9.5 mm die failed at 690 and 836 cycles
  - Three out of four (3/4) of the 280 I/O assemblies with 7.3 mm failed at 824,824, and 829 cycles
- The FPBGA failed at 5.7 mm maximum deflection under static bending load. It survived more that 300,000 mechanical cycles to maximum deflection of 0.625 mm (0.025"). This value decreased to about 100,000 cycles when packages were locally heated.
- The trend on the effects of die size, when sizes were far apart, could be possibly detected by the use of accelerated mechanical cycling and local heating of package possibly due to heating and rigidity differences in loading. Accelerated mechanical test detected the degradation effect of assemblies subjected to isothermal aging at 150°C for 20 minutes. Thus, such tests may be effective in screening of manufacturing defects, severe degradation due to environmental exposure, and mechanical robustness for application.

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REFERENCES

1. Ghaffarian, R., "*Chip Scale Packaging Guidelines*" distributed by Interconnection Technology Research Institute, http://www.ITIR.org, (512) 833-9930

2. Ghaffarian, R., Nelson, G, Cooper, M., Lam, D., Strudler, S., Umdekar, A., Selk, K., Bjorndahl, B., Duprey, R., *"Thermal Cycling Test Results of CSP and RF Package Assemblies"*, The Proceedings of Surface Mount International, Chicago, Sept. 25-28, 2000

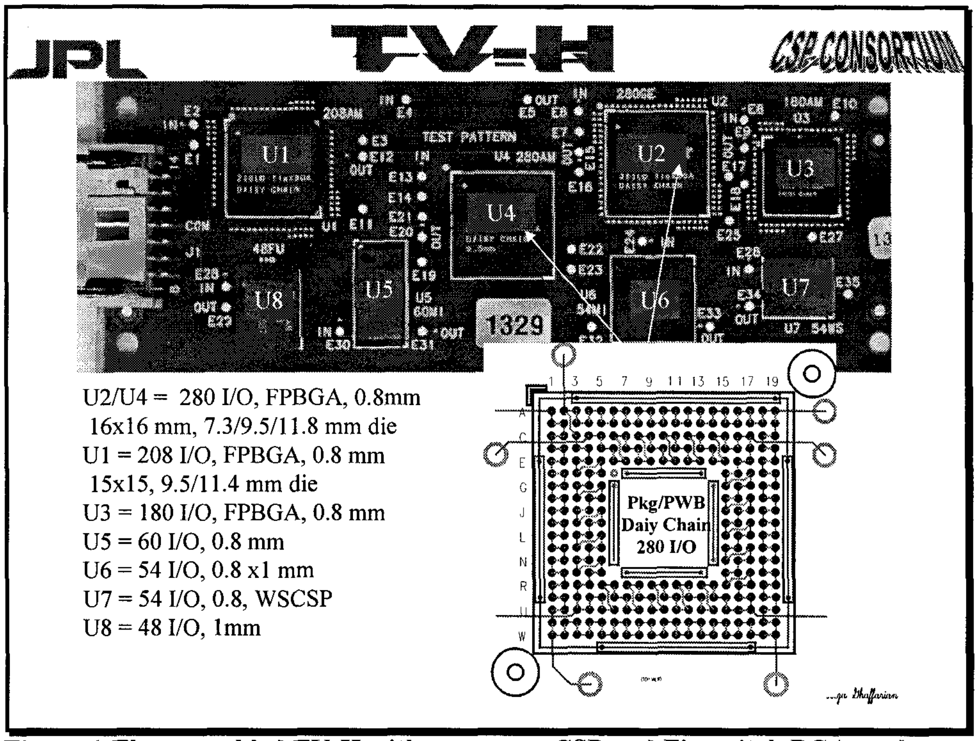

Figure 1 The assembled TV-H with numerous CSP and Fine pitch BGA packages. The package/PWB daisy chain for the 280 I/O FPBGA is shown on the bottom right.

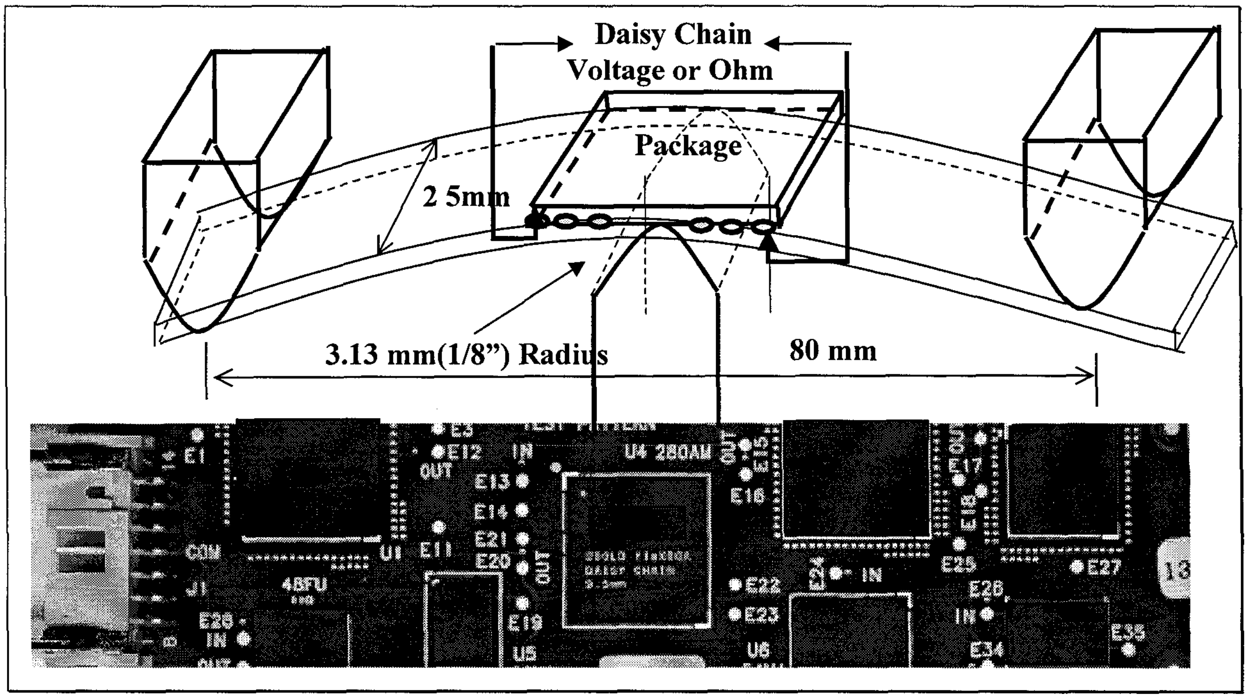

Figure 2 Three point bend test specimen and deflection mechanism

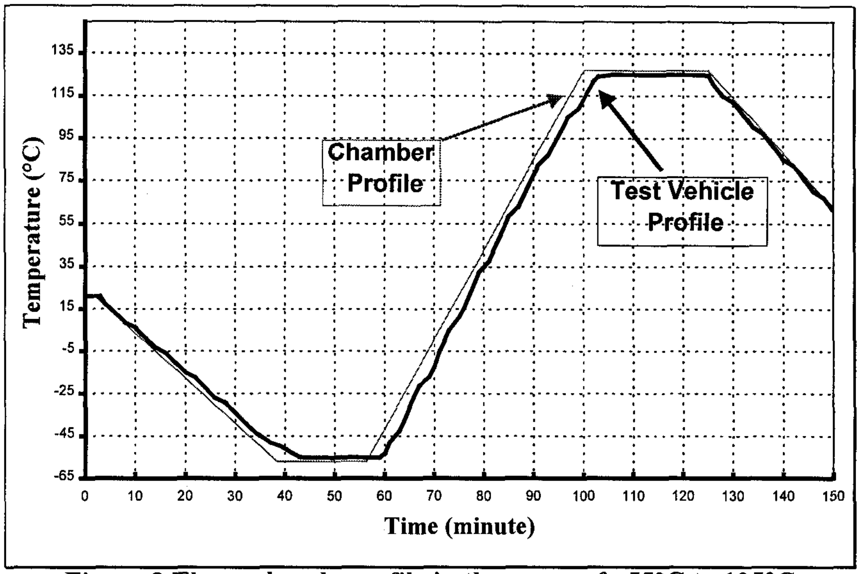

Figure 3 Thermal cycle profile in the range of –55°C to 125°C

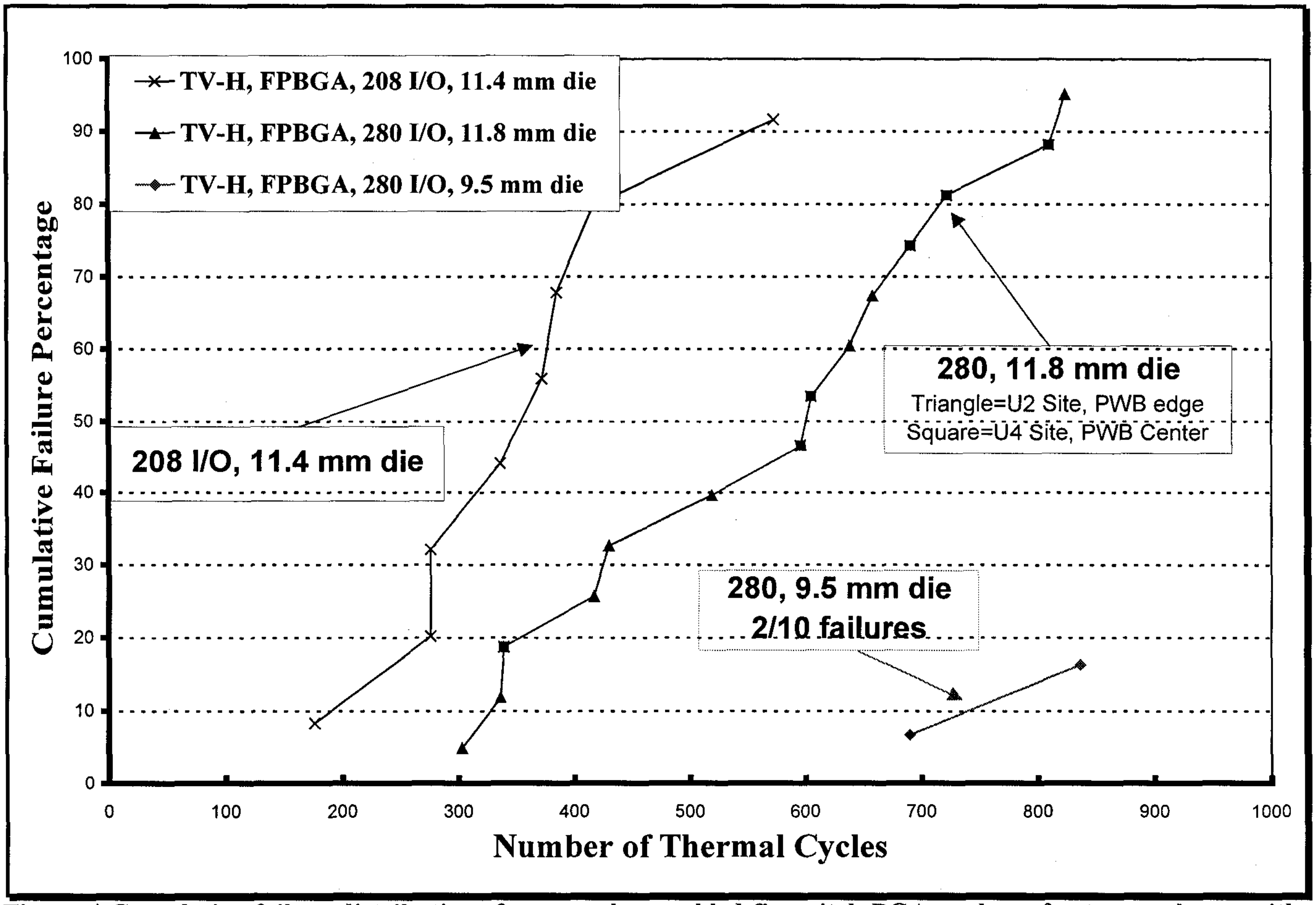

Figure 4 Cumulative failure distributions for several assembled fine pitch BGA package for two packages with 208 and 280 I/Os and three die sizes subject to 900 thermal cycles (-55/125°C)

Table 1 Static and mechanical cycles-to-failure for the 280 I/O fine pitch BGA with three die sizes under various cycling conditions

ID	Voltage (Ohm)	Die Size (mm)	0.025" (0.625 mm) Deflection	0.050" (0.125 mm) Deflection	0.075" (1.875 mm) Deflection	Comments
1A	N/A	11.8	N/A	N/A	N/A	Static, max. deflection 5.65 mm (0.226")
3C	N/A	9.5	>300,000	N/A	N/A	One deflection only
3A	N/A	11.8	N/A	10.000	6,470	6,470-7,691 cycles
4B	N/A	9.5	10,000	10.000	6,384	6,384-8,595 cycles
5B	N/A	7.3	N/A	10,000	8,450	8,450-10,204 cycles
2C	N/A	11.8	N/A	10,000	900	900-1490 cycles, **Age at 150°C, 20 min.**
2D	N/A	11.8	N/A	10,000	2,984	2,984-3,109, **Age at 150°C, 20 min.**
3B	4 (3.2)	11.8	104,361	N/A	N/A	One deflection only
1D	4 (3.2)	11.8	10,000	2,764	N/A	2,764-2,764 cycles
4A	4 (3.2)	9.5	10,000	1,460	N/A	1,460-1865 cycles, 10,000 @ .005"
5 A	4 (3.3)	7.3	10,000	2,846	N/A	2,846-3,175 cycles