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CSP drop test performance comparison for different solder ball materials

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CSP DROP TEST PERFORMANCE COMPARISON FOR DIFFERENT SOLDER BALL MATERIALS

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by

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ABSTRACT

CSP DROP TEST PERFORMANCE COMPARISON FOR DIFFERENT SOLDER BALL MATERIALS

By Won Chang

The drop test performance of CSP packages with two solder ball materials (Sn/Pb and Sn/Ag/Cu) in combination with three different ball pad finishes (Ni/Au with plating tails, Ni/Au with no plating tails, Cu-OSP) was compared. The test vehicle was 10 x 10 mm CSP packages with a 4-layer BGA substrate, and 168 balls. The drop test was done at zero hour and after high temperature bake for 500 and 1000 hours at 150°C to assess the influence of thermal aging on drop test performance. The results of this study showed that the CSP packages with eutectic solder balls had a mean drop cycle life 1.6 times higher than the packages with Pb-free solder balls. The CSP packages with Ni/Au ball pad finish had a 30% longer mean drop cycle life than the packages with Cu-OSP pad finish.

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List of Acronyms/Abbreviations

BGA	Ball Grid Array
CSP	Chip-scale BGA package
DOE	Design of Experiment
EDX	Energy Dispersive X-ray Spectroscopy
FA	Failure Analysis
FLGA	Fine-pitch LGA
HAST	Highly Accelerated Stress Test
HTS	High Temperature Storage
IC	Integrated Circuits
JEDEC	Joint Electron Device Engineering Council
LGA	Land Grid Array
MPa	megapascal
NSMD	Non-Solder-Mask-Defined
OSP	Organic Solderability Preservative
PCB	Printed Circuit Board
PDA	Personal Digital Assistant
PTH	Plated Through Hole
QFP	Quad-Flat-Package
SEM	Scanning Electron Microscopy
SMD	Solder-Mask-Defined
TFBGA	Thin-profile Fine-pitch BGA
TQFP	Thin QFP
VFBGA	Very-thin-profile Fine-pitch BGA

1 INTRODUCTION

The semiconductor integrated circuit (IC) industry has been growing steadily for the last few decades as applications for semiconductor devices have broadened to include almost everything from personal computers to telecommunications, home appliances, and automobiles. Annual sales have grown steadily, as shown in Figure 1. Semiconductor devices include IC chips of microprocessors, memories, programmable logics, graphics, networking, telecommunications, etc. As their applications were broadened, the requirements for IC packages have changed significantly. The increase in pin count and high density requirements for devices like microprocessors and graphics chips brought multi-layer ball grid array (BGA) packages to the mainstream in the packaging industry; this is a significant transition from the traditional lead-frame based packages. Now BGA packages have become the most common and high volume package configuration for all applications because of its high interconnect density, low cost, and easy handling due to the absence of leads.

Advancements in computer and telecommunication technologies made handheld products very popular. Cell phones, pagers, digital cameras, and personal digital assistants (PDA) are among the most popular handheld products. Especially in recent years, the growth in the cell phone industry has been explosive as wireless telecommunication technologies advance and more people start owning cell phones. The sales projection for 2004 is 17% ($38.9 billion) of $214 billion IC sales, as shown in Figure 2.

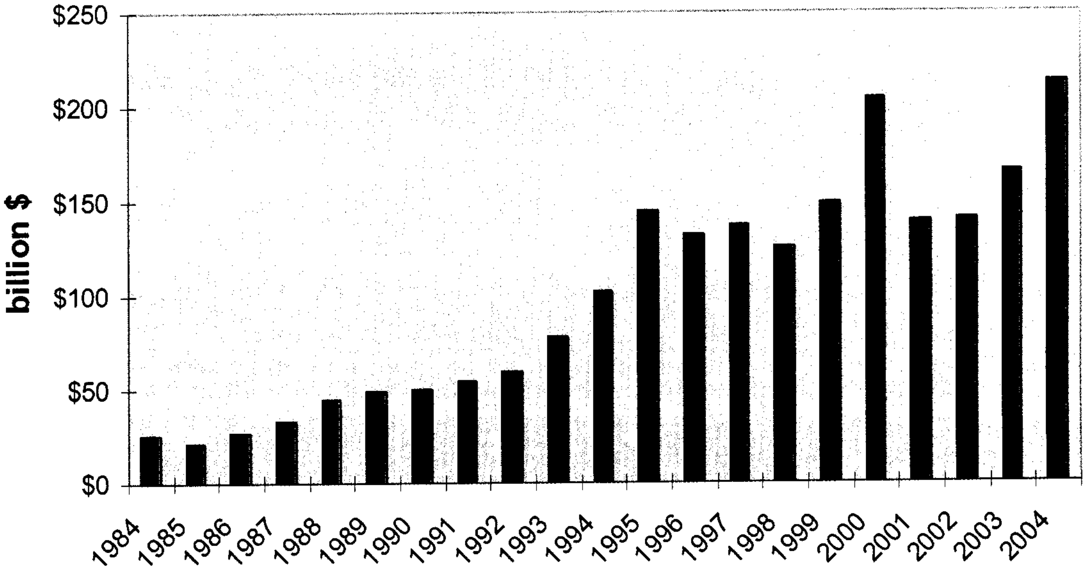


Figure 1. Annual worldwide semiconductor IC sales [1].

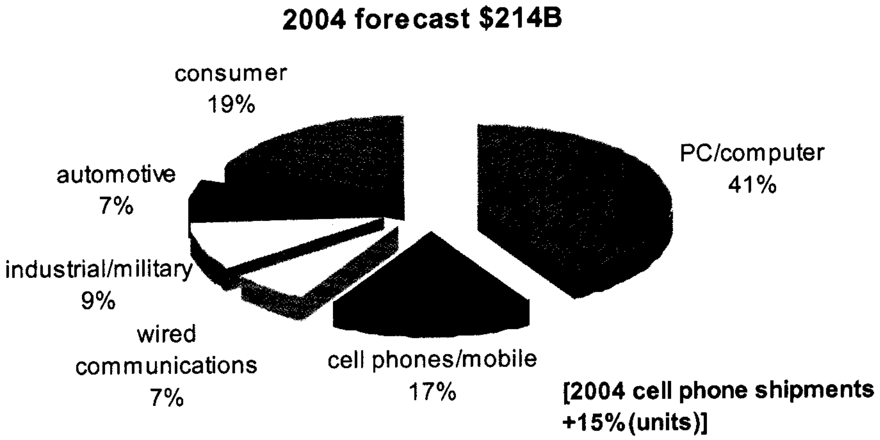


Figure 2. Semiconductor IC growth in 2004 [2].

Handheld products are, in general, thin and small in physical size, light-weight, and low in power consumption. The chip-scale (CSP) BGA package is one of the most commonly used packages in handheld products since it is inexpensive and can meet the high interconnect density requirement. Handheld products are prone to be dropped and damaged by mechanical shock and vibration due to the nature of their applications. Dropping finished products or subassemblies from a certain height is the most common way of evaluating drop resistance. The other commonly used test is a 3-point board bending test, which is done to evaluate the stress from board bending as a result of dropping [3]. In this study, the board level drop test was done per industry standard, i.e., JEDEC (Joint Electron Device Engineering Council) JESD22-B111 test methods were followed [4]. The JEDEC standard provides a standard method to measure drop test performance of handheld components. Specified in this standard are test board construction, material, size, and design rules, board layout and component locations, sample size for the test, impact pulse duration and g force, and test procedure. Using this standard, different components and materials can be evaluated or compared under the same test setup and procedure, since most key variables are fixed. Even though studies have been done to compare different solder ball materials for drop test performance, no study has been done to compare board level drop test performance from different ball pad finishes on CSP. In this study, two solder ball materials and three different ball pad finishes were compared when the board level drop test was done using 10 x 10 mm CSP packages as the test vehicle.

2 LITERATURE REVIEW

There are several types of drop tests. Product drop tests and board level drop tests were reviewed. The factors affecting board level drop test performance were also reviewed.

2.1 WHAT IS A DROP TEST?

A typical drop test consists of dropping a specimen from a certain height onto a surface. The dropping itself is a free fall. A test fixture is used to control the drop height as well as orientation of the specimen during the drop test. The surface can be made of concrete, marble, granite, or metal. A specimen is dropped directly onto the striking surface or is mounted on a drop table which hits the surface. A specimen can be components mounted on a printed circuit board (PCB) or a finished product such as a cell phone. One drop cycle can be one drop or multiple drops, depending upon the test requirements. After each drop cycle, the specimen is visually inspected for defects and also tested for functionality. The drop cycle continues for a fixed number of cycles or until the specimen fails.

2.2 WHY A DROP TEST?

Handheld products are prone to be dropped and damaged due to the nature of their applications. So, the drop test is designed to simulate real life failure in an accelerated manner. Shock from a drop test can cause excessive bending to the board and cause cracks along the solder joints which connect the CSP to the board. Cracks in solder joints will increase electric resistance or cause electrical continuity failures.

There are subtle differences between the drop test and other tests such as thermal shock, temperature cycle, highly accelerated stress test (HAST), or high temperature storage test (HTS). These latter tests are done to simulate defects arising from high temperature, high moisture, or rapid temperature changes. The drop test, however, is done at room temperature and normal moisture environment in which the handheld products are usually used. The drop test is also relatively quick while the other tests can take weeks to months to complete. Also, defects from drop tests are sensitive to component location on the board, while defects from other tests are not necessarily so.

2.3 PRODUCT DROP TEST

The product level drop test is more complicated than the board level drop test as there are many components in a product. A product like a cell phone can be considered a rectangular box with 6 faces, 12 edges, and 8 corners. So, a product can be dropped in many different ways. One of the major problems in a product drop test is controlling the orientation of the product during the test. Impact angles can change up to 30° to 40° if the setup is not right. According to a computer simulation, the impact stress can differ up to 34% when impact angles change within $\pm 5^{\circ}$ in the case of a cell phone drop test, as shown in Table 1 and Figure 3 [5]. In previous studies [5-12], specially-designed drop test platforms were built. The test platforms not only provided controlled drop angles but also were able to produce repeatable results.

Table 1. Impact Angles and Maximum Stress from a Cell Phone Drop Test [5].

Impact Angle	Simulated Max. Stress (MPa)	Absolute Difference from 32° test (%)
27°	28.0	34.6
28°	22.6	8.7
29°	21.6	3.8
30°	22.5	8.2
31°	20.7	0.5
32°	20.8	0.0
33°	19.6	5.8
34°	20.0	3.8
35°	20.8	0.0
36°	21.2	1.9
37°	22.4	7.7

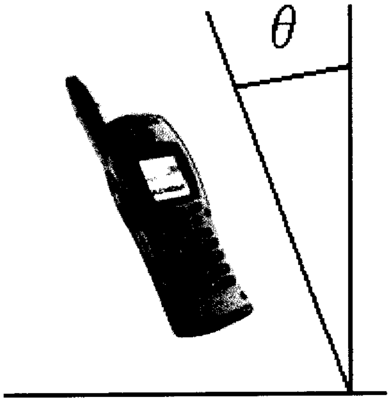


Figure 3. Drop angle for a cell phone drop test.

The strain of a board inside a cell phone was measured when the cell phone was dropped with different impact orientations and drop heights onto a steel plate [6]. A specially-designed drop tester was used to maintain the specimen in any specified orientation during the drop test. Strain gauges mounted at the center of the board showed positive strain and negative strain over time; this reflects the board bending outwards and inwards during the impact.

A correlation between the board level drop test and the cell phone drop test was attempted using a 308 pin land grid array (LGA) package [7]. Both a board and a cell phone were "free fall dropped" onto a concrete floor from a height of 1.5 m. The board drop showed much higher acceleration but lower plastic strain at the LGA solder joints than the product drop did. This is because the board was not supported by any screws while the LGA in the cell phone had screws along its edges.

2.4 BOARD LEVEL DROP TEST

Since every handheld product has at least one board mounted inside its mechanical housing, the board level drop test is a natural extension of the product drop test. The board level drop test is done to improve the final product reliability by understanding the design weakness at the component level. The test is less complex than the product drop test, as it deals with fewer components. Also, controlling many variables in the board level drop test is much easier, including the drop angle.

2.4.1 TYPES OF BOARD LEVEL DROP TEST

In a controlled pulse drop test, a test fixture, such as the one shown in Figure 4, is used to control the impact pulse and acceleration or g force. The test board is mounted onto a drop table with screws, which allows the board to bend when the drop table hits the strike surface. The board's potential energy is converted to kinetic energy during the free-fall drop.

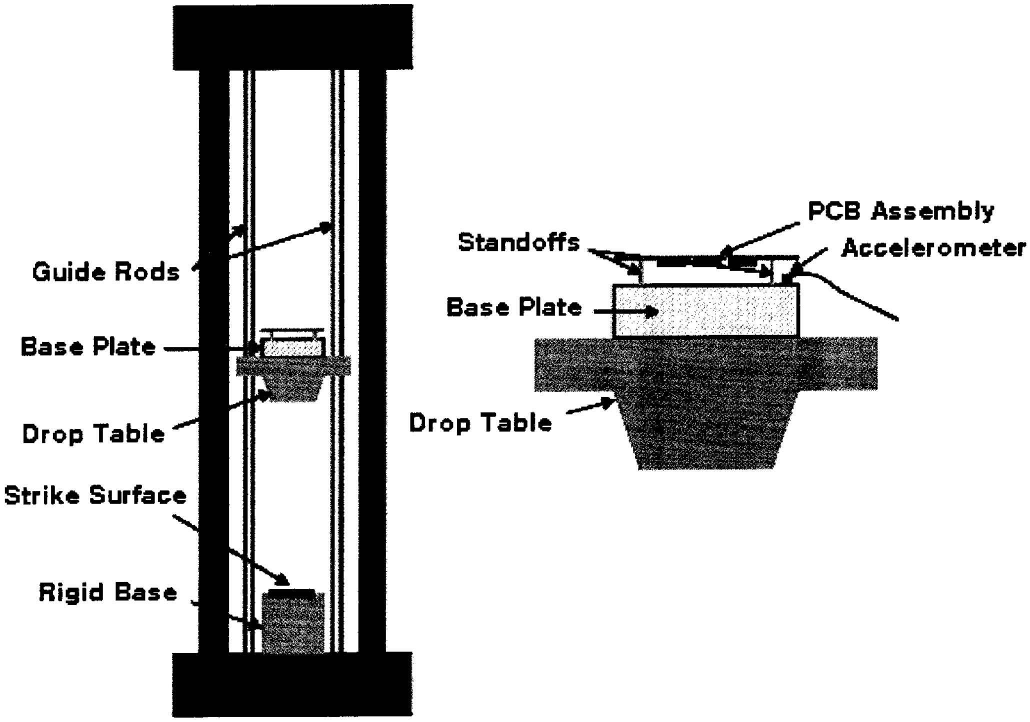


Figure 4. A drop test fixture [4].

The impact pulse generated by the kinetic energy is shown in Figure 5 and is expressed in Equations (1) and (2), where A_o is the maximum acceleration, t_w is the pulse width, H is the drop height, g is the acceleration due to gravity, and C is the rebound coefficient (1.0= no rebound, 2.0= full rebound).

$$A(t) = A_o \sin\left(\frac{\pi t}{t_w}\right)$$ Equation 1

$$\sqrt{2gH} = \frac{2A_o}{C}\frac{t_w}{\pi}$$ Equation 2

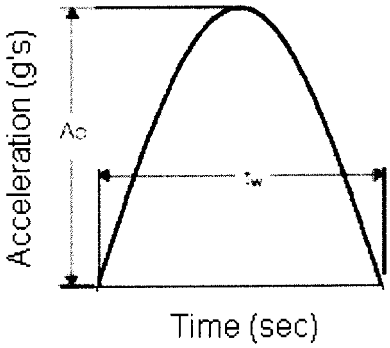


Figure 5. Typical impact pulse [4].

Specific g levels can be obtained by adjusting H and C, where C is highly dependent on the strike surface. The components mounted on the board are tested for changes in electrical resistance during or after the drop test. The drop test continues until a specified number of drops are met or until the components fail. In order to simulate the worst case drop impact, the board is held horizontally during the controlled pulse drop test and the components are usually mounted on the bottom side of the board. Results from the controlled pulse drop test are more reliable and reproducible as major factors affecting the drop test performance are controlled. A good repeatability of impact pulse and dynamic strains in a test board is shown in Figures 6 and 7, when a 100 x 48 x 1.6 mm board with 10 mounted components was dropped 6 times from a height of 1.5 m [8].

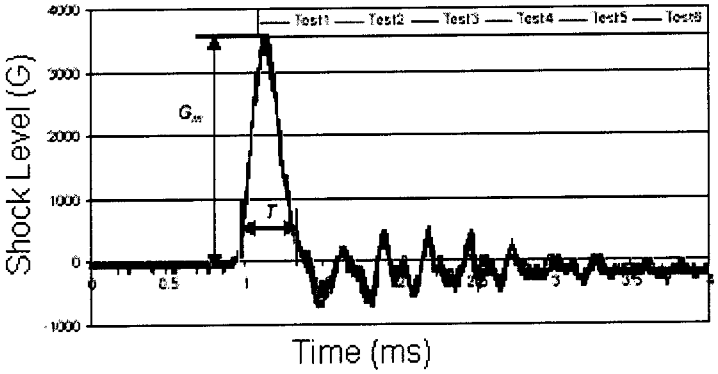


Figure 6. Impact pulse repeatability [8].

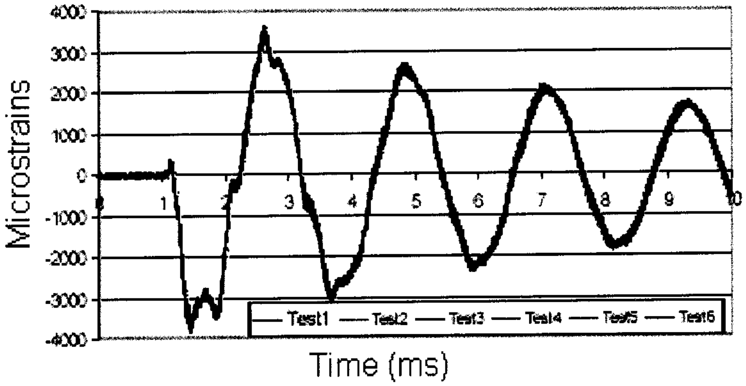


Figure 7. Repeatability of dynamic strains in PCB length direction [8].

The test board can be dropped vertically or horizontally. The board is dropped freely from a fixed height in both cases. Components are mounted on the top side of the board for the horizontal drop test. Examples of a vertical drop test and horizontal drop test are shown in Figures 8 and 9, respectively. In this example, a test board is held by vacuum nozzles which are part of the drop head. The board and drop head are dropped from a height of 150 cm. When the drop head passes a sensor at 85 cm, the vacuum releases the board. One drop cycle consists of one vertical and horizontal drop. The electrical resistance on a daisy chained board is measured between drop cycles. The test continues until the component drops off from the board [9]. The drop test can also be done while holding the test board at a predetermined angle. The test board is mounted on a jig and the jig is dropped down along guide rods. However, it is not easy to hold the test board at a fixed angle while the board is dropped repeatedly because of the heavy weight of the jig and the friction between the guide rods and the jig. In order to fix this problem, a hemisphere was added at the bottom of the test board, providing repeatable results of board deformation after the drop test [10].

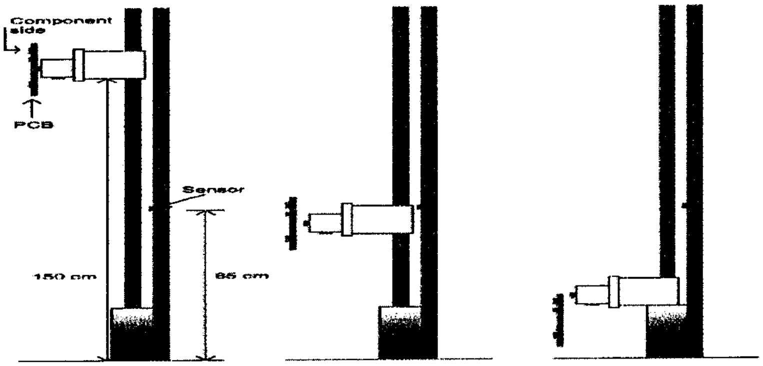


Figure 8. An example of vertical drop test [9].

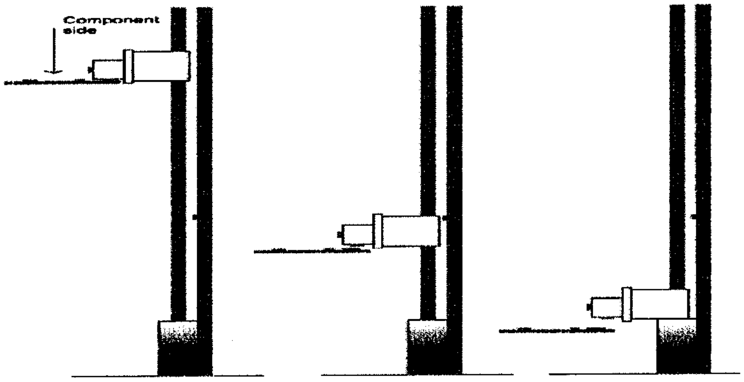


Figure 9. An example of horizontal drop test [9].

2.4.2 VARIABLES AFFECTING BOARD LEVEL DROP TEST PERFORMANCE

As shown in Equation (2), the acceleration is proportional to the drop height. In a simulation [11], a 100 x 48 mm board mounted on a base plate with 4 screws, with 10 TFBGA46 packages mounted on one side of the board, was dropped with its components facing down. As the drop height was increased from 0.5 m to 1.0 m, the peak acceleration was increased 1.7 times but the mean impact life was reduced from 19 drops to 5 drops, as shown in Table 2.

Table 2. Drop Height, Acceleration, and Mean Impact Life of TFBGA46 [11].

Drop Height (m)	Peak Acceleration (g)	Mean Impact Life (number of drops)
0.36	1500	42
0.5	2038	19
0.8	2900	9
1.0	3516	5
1.5	4532	3

For the same ball count and package body size, overall package thickness and solder ball standoff height are important. When the mean impact life between two packages of TFBGA46 and VFBGA46 with the same ball count of 46, ball pitch of 0.75 mm, package body size of 6.39 x 6.37 mm, and same die size of 4.6 x 3.5 mm from face-down drop tests was compared, TFBGA46 had slightly longer impact life than VFBGA46. This was most probably due to the fact that the TFBGA had higher solder standoff height and thicker mold compound, as shown in Table 3 [11].

Table 3. Mean Impact Life Comparison between TFBGA46 and VFBGA46 [11].

Package	Mold Cap Thickness	Solder Ball Standoff	Mean Impact Life (number of drops)
TFBGA46	0.6 mm	0.235 mm	30
VFBGA46	0.45 mm	0.17 mm	22

The impact pulse generated by the drop test is converted to cyclic up and down bending of the board, resulting in solder ball plastic strain. The plastic strain is higher with a 4-screw support than with a 6-screw support [11, 12]. When the solder joint stress was compared between packages mounted at the board corner and packages mounted at the board center, it was found that center packages had solder joint stresses 5 times higher than corner packages for a 4-screw supported board and 2 times higher for a 6-screw supported board [11]. When 3-point bending tests were done for the same size and thickness boards, the failure rate of a FR-4 board was higher than that of a build-up board, as the build-up board was more rigid and thus exerted less stress on the solder ball joints [3].

SnAgCu solder balls on TFBGA46 failed sooner than SnPb [11], which was different from the board level temperature cycle results [13]. The failure mechanism was different for both cases. Fatigue and shear stress were the main causes for temperature cycle failures while sudden mechanical shock and board bending caused solder joint failures during drop tests. Drop tests were performed using daisy-chained quad-flat packages (QFP) with Cu lead frames having 4 different coating materials - Ni/Pd/Au, Sn/Bi2%, Sn/ Pb15%, and 100% matte Sn [9]. Sn95.5%/Ag3.9%/Cu0.6%

solder paste was printed on immersion silver and organic solderability preservative (OSP) finished boards and reflowed after sample packages were picked and placed. Sn/Bi2% had the highest number of drop cycles to component drop-off from the board, while Ni/Pd/Au had the lowest. For the number of drop cycles to electrical failure, Sn/Bi2% had the highest while other coatings were lower and had similar number of cycles to failure. Information on the board construction, component layout, and material properties were not provided.

Ball shear tests on solder balls with four different compositions were used to compare shear force and failure modes when shear speed changed from 1 mm/min to 3 m/min [14]. The shear force at low speed was similar for both eutectic Sn/Pb and Sn95.5%/Ag3.8%/Cu0.7% balls. However, at the high speed, the shear force of Sn/Ag/Cu was less than one third of that of Sn/Pb, as shown in Table 4. The results suggest a potential problem with the Sn/Ag/Cu solder balls during drop impact.

Table 4. Solder Ball Shear Force at Low and High Shear Rates [14].

Material	Shear Force (N)	
	Shear Speed = 1 mm/min	Shear Speed = 3 m/min
Sn63%/Pb37%	10.6	54
Sn96.5%/Ag3.5%	11.7	52
Sn95.5%/Ag3.8%/Cu0.7%	12.9	16
Sn96.2%/Ag2.5%/Cu0.8%/Sb0.5%	13.2	22

In the case of the controlled-pulse drop test in which the board is held horizontally, impact pulses cause the board to bend up and down. The impact pulse and dynamic strains of the board in a longitude direction, respectively, are shown in Figures 6 and 7 when a test board of 100 x 48 x 1.6 mm with 10 mounted TFBGA46 packages was dropped from a height of 1.5 m. Figure 7 shows greater dynamic strains in the negative directions than in the positive directions, which signify there was more board warping during the negative bending cycles. In addition to board bending, the inertial force of the package also caused the face-down components to fail sooner during the drop test. As shown in Table 5, the mean impact life of TFBGA46 packages in a face-up configuration was 5 times longer than that in a face-down configuration.

Table 5. Mean Impact Life from TFBGA46 Face-up and Face-down Drop Test [11].

Package Type	Drop Orientation	Mean Impact Life (number of drops)
TFBGA46	Face down	6
TFBGA46	Face up	30

Horizontal drop is worse than vertical drop. When FLGA308, a land grid array package with 308 pads at a pitch of 0.8 mm, was tested, there was a plastic strain of 0.036 from horizontal drop tests and 0.012 from vertical drop tests. The board warpage was 0.09 mm for horizontal drops and 0.04 mm for vertical drops, at the location of the FLGA308 [7].

2.5 LITERATURE REVIEW SUMMARY

There are many variables in the drop test that affect the mean impact life, as summarized in Table 6. These include board size, thickness and material, component size and weight, drop height and mass, drop orientation, and where the components are mounted on board – top side or bottom side. Many attempts have been made to measure actual drop test performance or simulate it. However, they have failed to provide consistent and reproducible results because the variables used for each test or study were different every time.

Table 6. Variables in Board Level Drop Test.

Variable	Effect	Reference
Drop height	Higher drop height, shorter impact life	[11]
PCB material and pad finish	Build-up board has a higher bend stress level than that of bare FR-4.	[3]
Number of supports (screws) mounted on PCB	Solder joint stress of the component from board center is higher when the board is mounted with 4 screws versus 6 screws.	[11, 12]
Component package type	TFBGA46 has slightly longer impact life than VFBGA46.	[11]
	TQFP (thin qual flat pack) fails sooner than CSP.	[7]
Solder material	SnAgCu solder balls failed sooner than SnPb.	[14]
Drop orientation (component face up or down)	Component face-down drop has a shorter impact life.	[11, 12]
Drop orientation (vertical or horizontal)	Vertical drop has a shorter impact life.	[7]

3 STUDY HYPOTHESIS AND OBJECTIVE

3.1 HYPOTHESIS

The hypothesis of this study was that the CSP's drop test performance was a function of solder ball material and its ball pad finish, and that the number of drop tests before failure would be different for each solder ball-pad finish combination. The differences are expected since material properties such as intermetallic compound formation are key factors influencing the drop test performance.

3.2 OBJECTIVE

The objective of this study was to determine the best combination of solder ball material and ball pad finish by comparing the failure rate and failure modes from board level CSP drop tests. The combinations to be tested were Sn/Ag4%/Cu0.5% and Sn63%/Pb37% solder balls, with different ball pad finishes of Ni/Au with plating tails, Ni/Au without plating tails, and Cu organic solderability preserve (OSP) without plating tails. The failure mechanism was also investigated.

At present, Sn63%/Pb37% solder balls are most commonly used on CSP packages and the semiconductor industry is trying to change them to Pb-free solder balls, due to the toxicity of Pb [15]. Sn/Ag4%/Cu0.5% is one of the leading material compositions for Pb-free solder balls. Ni/Au finish with plating tails provides good bondability and costs less while Ni/Au without plating tails is good for high density routing. Cu-OSP is a low cost alternative to Ni/Au finish. The surface cleanliness is affected by each type of pad finish and may impact wire bondability and solder ball wetting to the pads. The wire pull test and solder ball shear test were used to measure the bondability and the wetting.

The contribution to CSP drop impact life of solder ball material and ball pad finish was determined by comparing the failure rate from the board level drop test. The failures were analyzed to determine if they were related with solder ball material, the ball pad finish, or a combination thereof.

4 EXPERIMENTAL PROCEDURE

A flow chart of the overall experimental approach is shown in Figure 10.

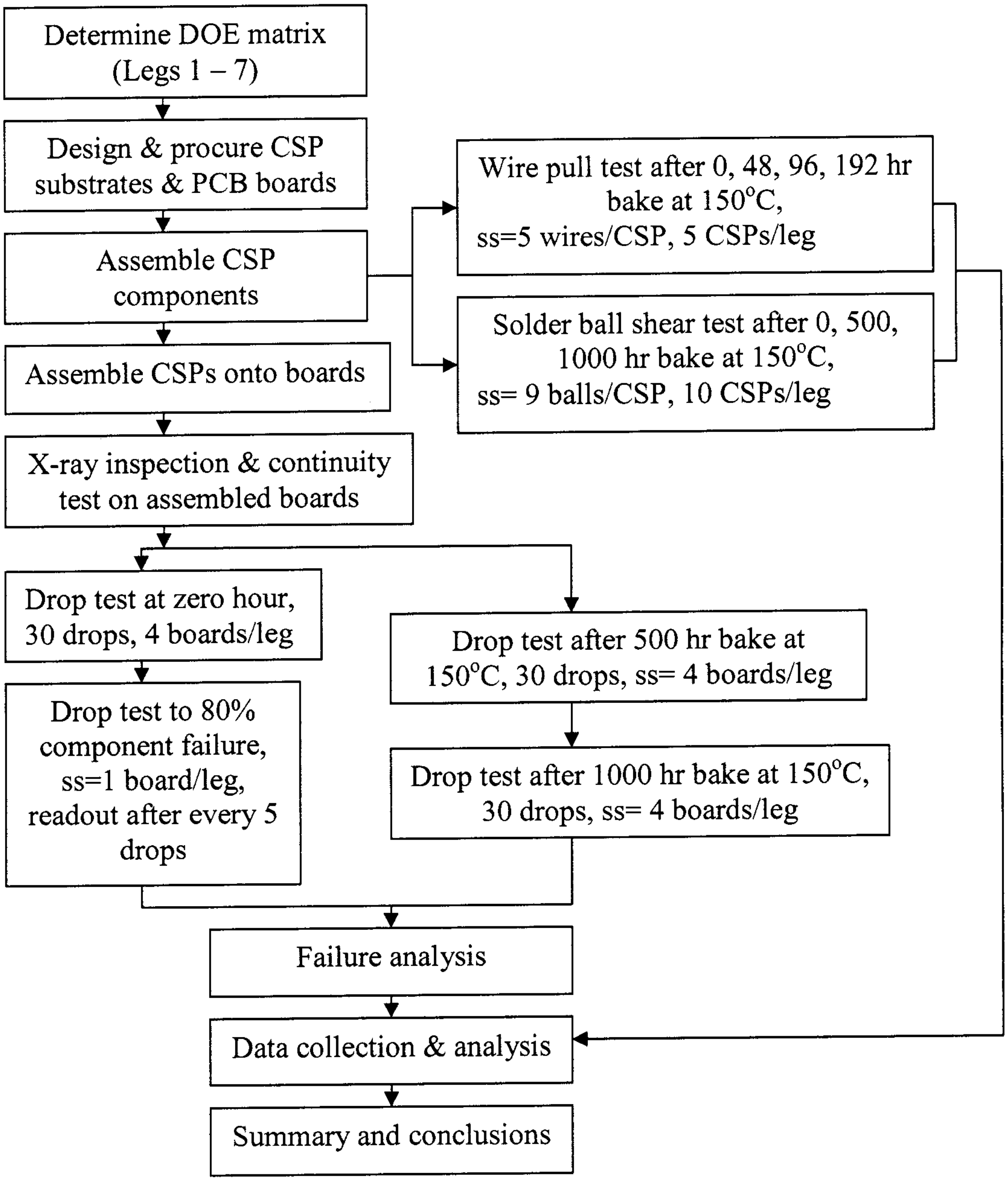


Figure 10. Experimental flow chart.

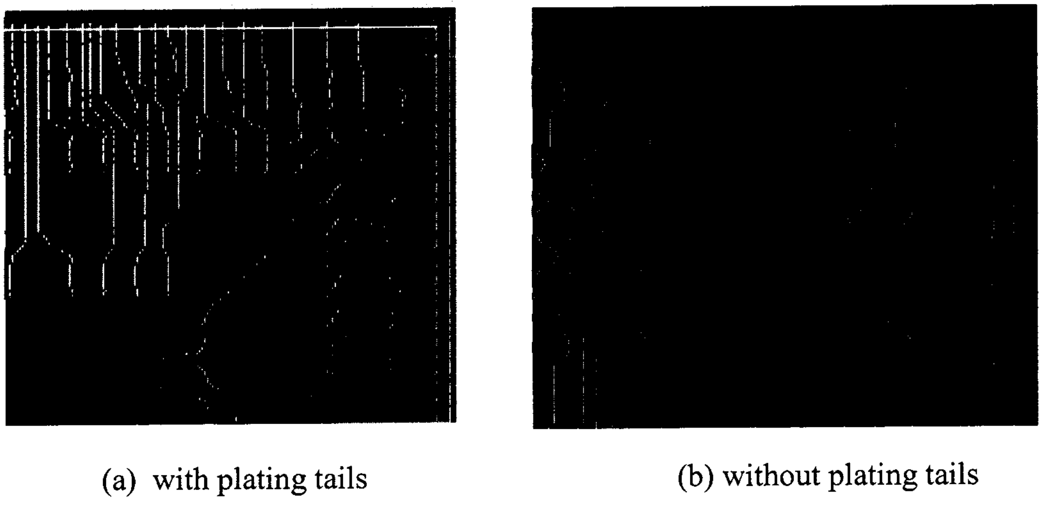
4.1 DESIGN OF EXPERIMENT MATRIX

The Design of Experiment (DOE) matrix is shown in Table 7. The matrix has 3 different pad finishes and 2 solder ball materials, combinations of which were evaluated and compared in this study. Each of 3 different pad finishes of Ni/Au with plating tails, Ni/Au without plating tails, and Cu-OSP without plating tails was paired with Sn/Ag4%/Cu0.5% Pb-free and Sn63%/Pb37% eutectic solder balls (Legs 1 – 6). Therefore, 2 solder ball materials can be compared for each pad finish and the 3 different pad finishes can be compared for each solder ball material. Board orientation during drop test was fixed to the via-in-pad side up for Legs 1 - 6. Leg 3 and Leg 7 were the same except for the board drop orientation, which was to compare drop test performance between the via-in-pad side up and the via-in-pad side down during the board drop test.

Table 7. DOE Matrix for Drop Test.

Leg	CSP Ball Pad Finish	Solder Ball Material	Board Orientation during Drop Test
1	Ni/Au with plating tails	Sn/Ag4%/Cu0.5% Pb-free	Via-in-pad side up
2	Cu-OSP without plating tails	Sn/Ag4%/Cu0.5% Pb-free	Via-in-pad side up
3	Ni/Au without plating tails	Sn/Ag4%/Cu0.5% Pb-free	Via-in-pad side up
4	Ni/Au without plating tails	Sn63%/Pb37% eutectic	Via-in-pad side up
5	Cu-OSP without plating tails	Sn63%/Pb37% eutectic	Via-in-pad side up
6	Ni/Au with plating tails	Sn63%/Pb37% eutectic	Via-in-pad side up
7	Ni/Au without plating tails	Sn/Ag4%/Cu0.5% Pb-free	Via-in-pad side down

Ni/Au is the most commonly used pad finish for wire bonded CSP packages today. Plating Ni/Au on both sides of the substrates at the same time, during the substrate manufacturing process, is easy and cost effective. The Ni/Au coating prevents the Cu in the solder ball pads from being oxidized. OSP is a relatively new finish for CSP substrates. The OSP also covers the Cu on the ball pads, preventing the Cu from being oxidized, and is removed during the ball attach process at CSP assembly. A typical substrate manufacturing process flow is, for Ni/Au with the plating tails and without plating tails, shown in Appendixes A and B, respectively. During substrate manufacturing, the substrates are processed in the form of a panel. One panel can hold hundreds of substrates, depending upon the substrate size. Plating tails are extra trace lines which connect all of the substrates within a panel for electrical connections for plating. For substrates without plating tails, the plating tails are removed after the Ni/Au plating. Examples of substrate design with and without plating tails are shown in Figure 11.



(a) with plating tails

(b) without plating tails

Figure 11. Substrate design examples with and without plating tails.

The Ni/Au plating is the last step in the process for making substrates with plating tails. So, the plated surface is clean. However, for the substrates without plating tails, chemical etching and cleaning is done to remove the plating tails after Ni/Au plating. Depending upon how well the cleaning is done after the chemical etching, the Ni/Au plated bond fingers may not be as clean as those of the substrates with plating tails. Therefore, wire bondability may become questionable for the substrates without plating tails. In general, the substrates with plating tails are less expensive and better for bondability, while the substrates without plating tails are better for electrical performance of high speed products, due to the absence of the antenna effect. Electrical continuity tests can be done on the substrates without plating tails before IC assembly begins so that expensive IC chips do not have to be thrown away due to electrically shorted substrates.

4.2 SAMPLE SIZE

A total of 56 boards and 1680 components were required for this study. The sample size per leg is shown in Table 8. CSPs were mounted on both sides of the board, with 15 CSPs per side, for a total of 30 CSPs per board.

Table 8. Sample Size for DOE.

Number of components per board	30 (15 x 2 sides)
Number of boards per leg	8
Total number of boards for DOE	56 (8 x 7 legs)
Total number of components for DOE	1680 (30 x 56 boards)

4.3 MATERIALS AND DESIGN RULES FOR CSP AND TEST BOARD

Designs for components and test boards were done such that a daisy chain was formed when the components were mounted on the board. The component was a 10 x 10 x 1.2 mm CSP package with 168 balls. The pad design was solder-mask-defined (SMD). The CSP materials and design rules used in this study are shown in Table 9.

Table 9. CSP Materials and Design Rules.

Package type	CSP
Package size	10 x 10 x 1.2 mm
Ball count	168
Die size	5.4 x 9.0 mm
Bonding wire	Au, 22 μm diameter
Ball pitch	0.65 mm
Ball size	0.3 mm diameter
Number of layers, substrate	4 layers
Thickness, substrate	0.36 mm
Core material, substrate	BT HL-832
Solder resist material, substrate	PSR40000-AUS5
Ball pad design	SMD
Ball pad size, substrate	375 μm
Ball pad opening, substrate	275 μm
Thru-hole via size, substrate	100 μm
Thru-hole via pad size, substrate	250 μm
Line space	57 μm
Line width	45 μm

There were 3 types of substrates based on the DOE matrix - Ni/Au pad finish with plating tail, Ni/Au pad finish with no plating tail, and Cu-OSP pad finish with plating tail. The test board was 77 x 132 x 1.0 mm in size, had 4 screw holes, and was an 8-layer (1-6-1) build-up board. Fifteen components were mounted on each side of the board, with the double sided board having 30 components. The test board size and layout is shown in Figure 12 and the board cross-section is shown in Figure 13. The test board was designed according to JEDEC standard JESD22-B111 [4] requirements, as shown in Table 10. Side A had microvias in the pads (via-in-pad) while Side B had no via-in-pad. Twenty plated through holes (PTH) per square centimeter were populated within 1.2 times the area covered by the component. All routing and traces were done on layers 2 and 8. All component pads on the boards were non-solder-mask-defined (NSMD) and were covered by the OSP. The ball pad pitch was 0.65mm and the pad opening was 425 μm in diameter.

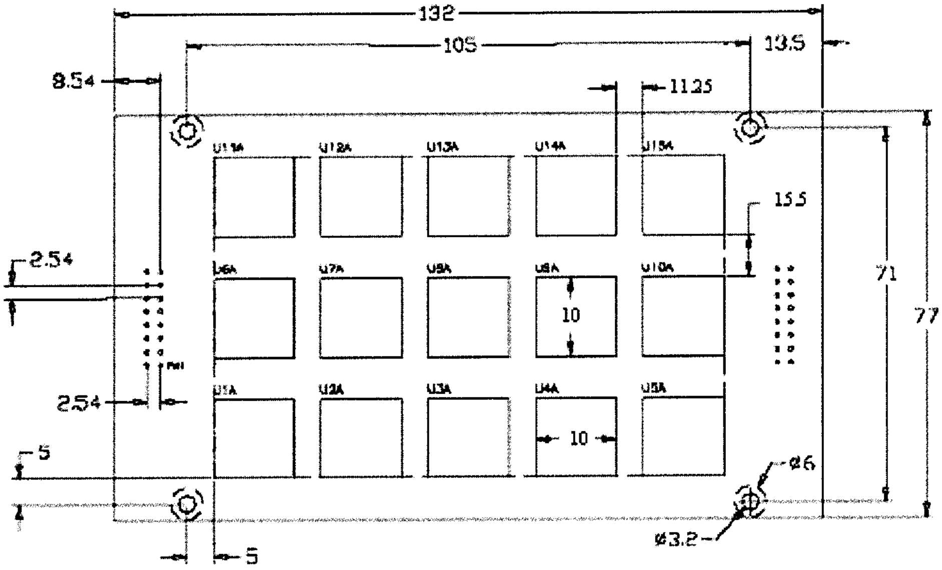


Figure 12. Test board size and layout, unit: mm [4].

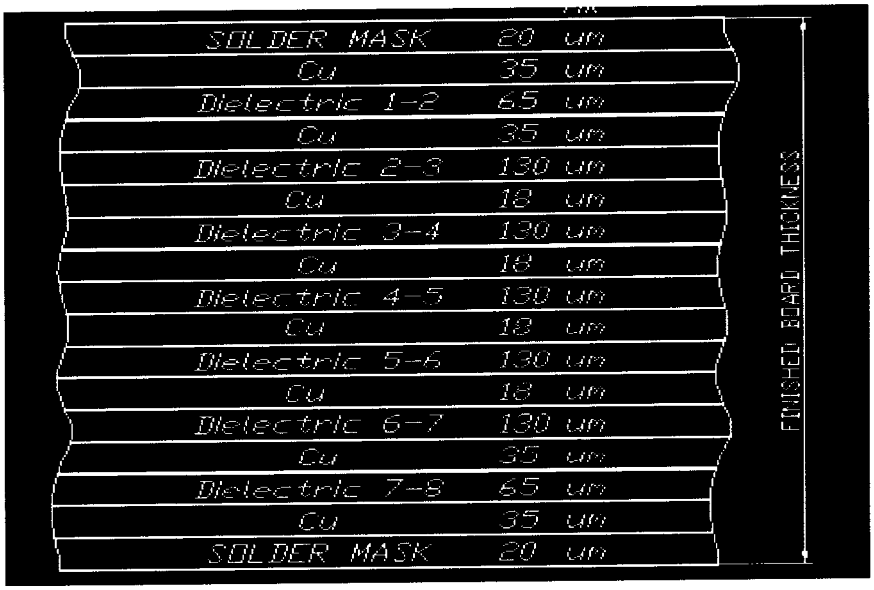


Figure 13. Test board cross-section.

Table 10. Test Board Materials and Design Rules.

Board size	77 x 132 x 1.0 mm
Number of layers	8 layers (1-6-1)
Core material	BT HL-832
Build-up material	ABF
Solder resistor material	Hitachi SR7000
Laser via size	110 µm diameter
Capture pad size	220 µm diameter
Thru-hole via size	300 µm diameter
Via land size	550 µm diameter
Number of PTHs within 1.2x the area covered by CSP	20 PTHs/sq. cm
Ball pad design	NSMD
Ball pad opening	425 µm diameter
Ball pad size	275 µm diameter
Ball pad finish	Cu-OSP
Ball pad pitch	0.65 mm
Line space	127 µm
Line width	75 µm
Layers for routing and traces	Layer 2 and layer 8

4.4 COMPONENT AND BOARD ASSEMBLY

The total of 1680 components and 56 boards were assembled according to Table 8. The component assembly and board assembly process for each leg of the DOE was the same except for the ball attachment and board mounting reflow temperature. Sn63%/Pb37% eutectic solder balls were reflowed at 223°C while Sn/Ag4%/Cu0.5% Pb-free solder balls were reflowed at 245°C.

A typical solder ball cross-section after board assembly is shown schematically in Figure 14. The pad on the board is NSMD and the pad on the substrate is SMD. The substrate pad shown in Figure 14 has a Ni/Au finish. In the case of Cu-OSP finish, the cross-sectional view is the same except for the absence of the Ni/Au layer between the solder ball and Cu pad.

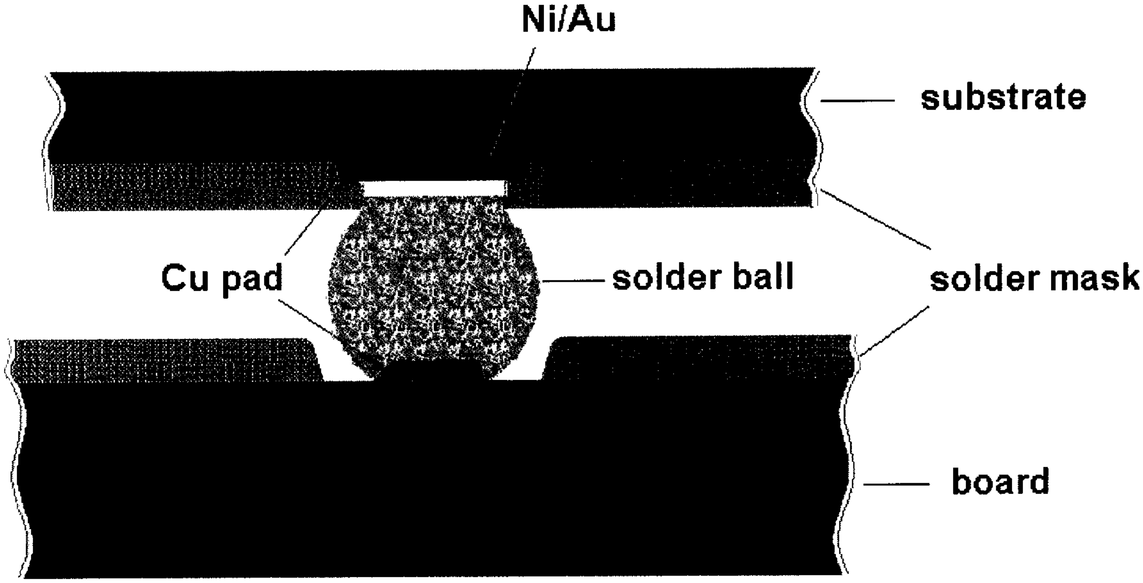


Figure 14. Solder ball cross-section after board assembly, shown for Ni/Au finished pad.

4.5 TEST

4.5.1 WIRE PULL TEST

The bond wire pull test was done to evaluate the effect of the three different ball pad finishes on wire bondability. The wire bonding was done from bond finger to bond finger using 22 μm diameter gold wire. Bonding a wire consists of two bonds - 1st bond and 2nd bond. The first bond is a ball bond which was done by applying a force and ultrasonic energy to a ball under the tip of a bonding tool, capillary, while the bond finger surface was heated to 180 ± 5°C. The second bond is a wedge bond which was done in same way as the first bond was done but without a ball. Five wires per CSP, 5 CSPs per pad finish, were pulled. The wire pull force and breaking failure modes were measured, documented, and compared. There are 5 possible failure modes, as shown in Table 11. This test was done after 0, 48, 96, and 192 hour bakes at 150 ± 5°C, after wire bonding.

Table 11. Failure Modes from Wire Pull Test.

Failure Mode	Description
A	Wire broken at mid span
B	Ball bond lifting cleanly from bond finger
C	Ball bond broken at ball neck
D	Wedge bond wire lifting cleanly from bond finger
E	Wedge bond wire broken at the heel of wedge bond

4.5.2 SOLDER BALL SHEAR TEST

The solder ball shear test was done to evaluate the adhesion of the eutectic and Pb-free balls to the three different pad finishes with shear tool speed of 0.5 mm/sec.

Nine balls per CSP were tested from 10 CSPs per leg. Ball shear force and shear failure modes were measured, documented, and compared. There are 4 possible failure modes, as shown in Table 12. This test was done after 0, 168, 500, and 1000 hour bakes at 150 ± 5°C, after ball attachment and singulation.

Table 12. Failure Modes from Solder Ball Shear Test.

Failure Mode	Description
A	Solder remaining on 90% to 100% of pad
B	Solder remaining on 10% to 90% of pad
C	Solder remaining on 0% to 10% of pad
D	Solder ball coming off with a metal layer underneath solder

4.5.3 X-RAY INSPECTION AFTER BOARD ASSEMBLY

After board assembly, X-ray inspection was done on the components mounted on the boards, to check for voids in the solder balls, ball-to-ball shorts, and other abnormalities. Electrical continuity test was also done on all boards. Only the boards passing X-ray inspection and electrical continuity test were used for the drop test.

4.5.4 DROP TEST

A King Design KD-DP1200 drop tester with a HP-34970A data acquisition system was used. A test board, with components mounted on both sides, was mounted with 4 screws on the base plate, as shown in Figure 15. An accelerometer was attached on the base plate and the data acquisition system. The drop height was adjusted, before the drop test began, to obtain a peak acceleration of 1,569 g and an impact pulse duration of 0.5 ms, as shown in Figure 16.

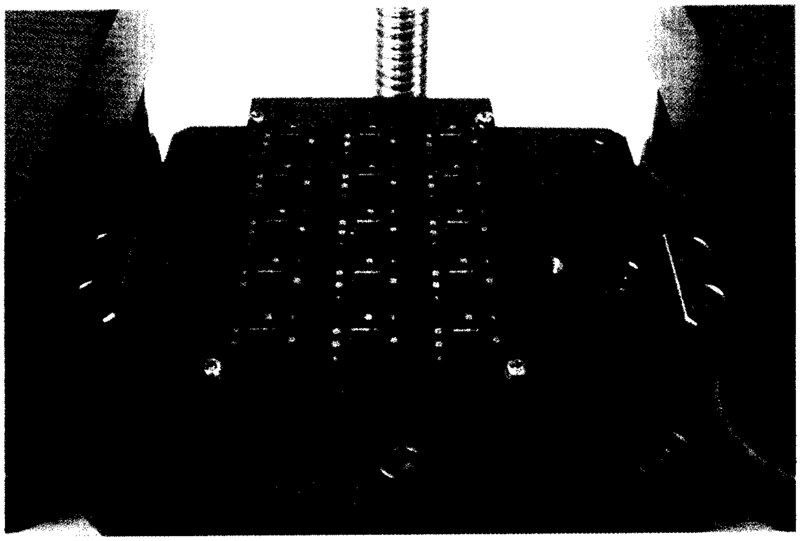


Figure 15. A test board mounted on base plate for drop test.

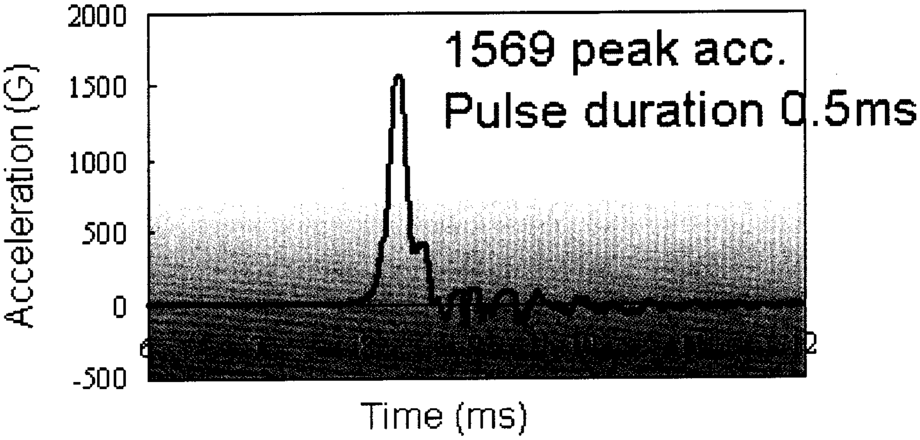


Figure 16. Actual peak acceleration and pulse duration used in this study.

Once pre-test characterization was complete, the board drop test began. Each board was tested with side B (no via-in-pad side) facing down (face-down test), except the boards for Leg 7 where each board was dropped with side B facing up (face-up test). The board was dropped 30 times after 500 hours and 1000 hours of high temperature storage, respectively. Each board was tested for electrical resistance prior to the drop test and again after 30 drops. A 20% or greater increase from the initial resistance value resulted in the component being classified as "failed". After 30 drops of zero hour test were done on 4 boards per leg, the test continued for one board per leg until 80% of the components on each side of the board failed. Each board, in this case, was tested for electrical resistance after every 5 drops.

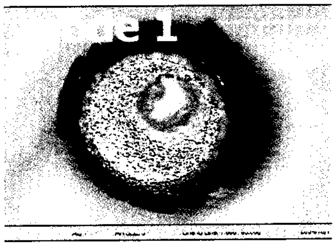
4.6 FAILURE ANALYSIS

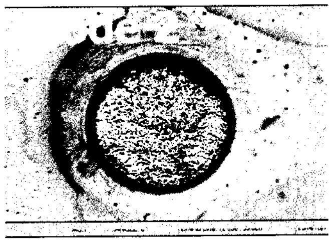
For each failed board, failure analysis (FA) was done to identify the failed component locations on the board as well as failed ball locations, if the balls failed. Further FA was done to identify the failure mode, namely failure at the substrate side or board side.

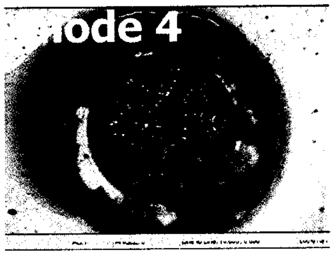
Red color dye penetrant chemical, DYKEM, was inserted between the substrate and the board and held at room temperature for 30 minutes. The failing component was then pulled off from the board. This is a so-called "dye and pry test", to identify the failure modes. There are 7 possible failure modes, as shown in Table 13. Every ball in the failing component was inspected under a 20X magnification microscope. Cross-sectional analysis was also done to identify the breaking interface along the failing balls and the intermetallic compound (IMC) thickness was measured and compared among Legs 1 - 6. What was also compared was solder ball standoff height after board mounting.

Table 13. Failure Modes from Dye & Pry Test.

Failure Mode	Failure Description	
1	Good (red dye covering 0% of substrate pad and board pad)	Refer to mode 1 photo.
2	Red dye covering less than 10% of substrate pad	Refer to mode 2 photo.
3	Red dye covering 10% to 90% of substrate pad	
4	Red dye covering more than 90% up to 100% substrate pad	Refer to mode 4 photo.
5	Red dye covering than 10% of board pad	
6	Red dye covering 10% to 90% of board pad	
7	Red dye covering more than 90% up to 100% board pad	







5 RESULTS

5.1 RESULTS OF WIRE PULL TEST

The average wire pull force for three different pad finishes is shown in Figure 17. The test result details are shown in Appendices C - F. All wires broke at the second bond with failure mode E, i.e., the wire broke at the heel of the wedge bond. About 5% degradation in pull force after 192 hour bake was observed but was similar among all three pad finishes. No significant difference in wire pull force and failure modes was found among the three different pad finishes. This means that there was no difference in wire bondability among the three different pad finishes.

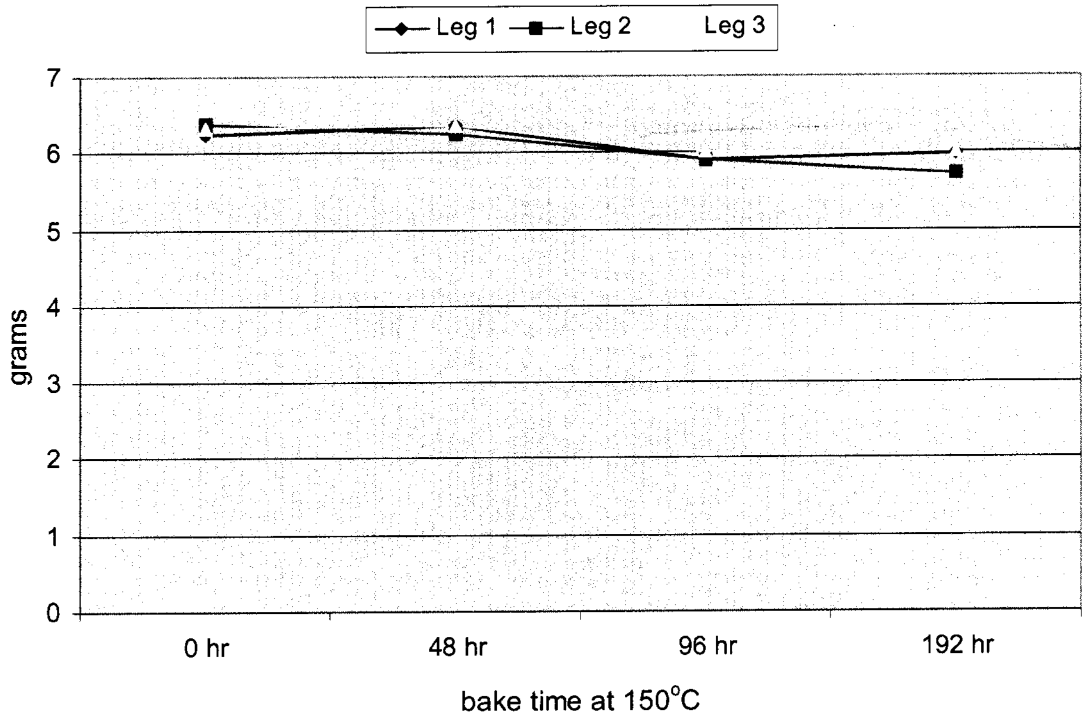


Figure 17. Wire pull force after high temperature bake.

5.2 RESULTS OF BALL SHEAR TEST

The average ball shear force is summarized in Table 14 and in Figure 18. All balls tested exhibited mode A failure, i.e., there was solder remaining on 90% to 100% of pad. The shear force of the Sn/Ag/Cu balls (Legs 1 – 3) was higher than that of the Sn/Pb balls (Legs 4 – 6) throughout the tests from zero hour to 1000 hour bakes. The Sn/Ag/Cu balls showed 19% higher ball shear force than the Sn/Pb balls at zero hour test. The average shear force of the Sn/Ag/Cu balls changed from 447 grams at zero hour to 400 grams after 1000 hour bake, an 11% decrease from the zero hour value. The Sn/Pb ball's average shear force changed from 375 grams at zero hour to 298 grams after 1000 hour bake, a 21% decrease from the zero hour value. The Sn/Ag/Cu ball's degradation in average shear force during the thermal aging was slower than the Sn/Pb ball's. Balls with the Cu-OSP pad finish had the lowest shear force and the highest thermal degradation over time, among the Sn/Ag/Cu balls. However, the Sn/Pb balls did not show much difference in average shear force among the 3 pad finishes.

Table 14. Average Ball Shear Force Data, unit: grams.

	0 hr	**168 hrs**	**500 hrs**	**1000 hrs**	**average**	
Leg 1	459	424	432	428	436	Sn/Ag/Cu ball
Leg 2	437	409	398	363	402	
Leg 3	446	423	438	409	429	
Leg 4	379	362	321	285	337	Sn/Pb ball
Leg 5	360	329	315	312	329	
Leg 6	386	348	312	296	335	
Sn/Ag/Cu ball	447	419	422	400	422	Ni/Ag + Cu-OSP
Sn/Pb ball	375	346	316	298	334	
Ni/Ag finish	453	424	435	418	432	Sn/Ag/Cu ball
Cu-OSP finish	437	409	398	363	402	
Ni/Ag finish	382	355	317	291	336	Sn/Pb ball
Cu-OSP finish	360	329	315	312	329	

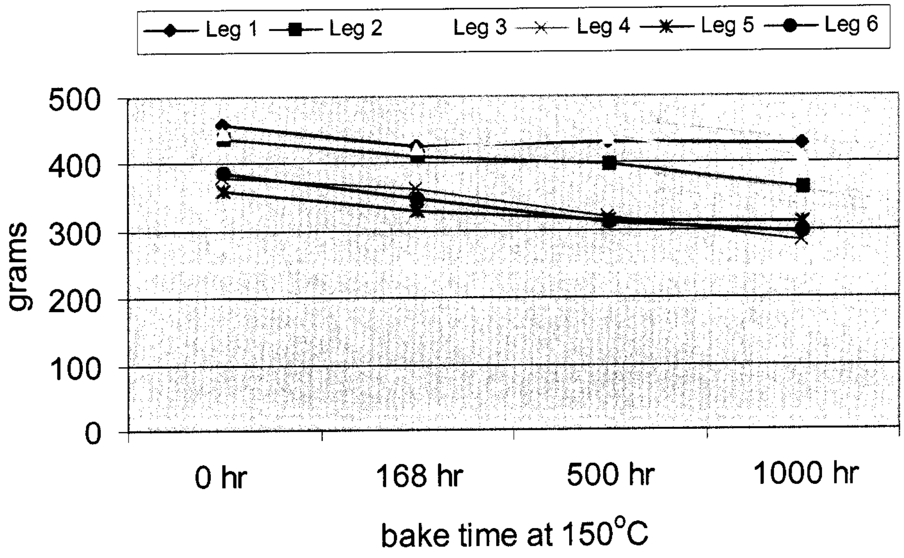


Figure 18. Solder ball shear force after high temperature bake.

5.3 RESULTS OF DROP TEST

5.3.1 RESULTS AFTER THE FIRST 30 DROPS

Four boards per leg were tested at zero hour. Another 4 boards per leg were tested after 500 and 1000 hours high temperature storage (HTS). Electrical resistance was measured after 30 drops at each readout point. The test results from the first 30 drops are summarized in Table 15. Details of electrical resistance data are shown in Appendices G – AV. There were no failures from zero hour and HTS 500 hour samples from all 7 legs. The Sn/Pb balls (Legs 4 - 6) had no failures from all tests, including after 1000 hours HTS. However, all samples with the Sn/Ag/Cu balls (Legs 1 - 3, Leg 7) failed after 1000 hours HTS. All failed components were from the face-down side of the boards. No components mounted on the face-up side failed.

Table 15. Drop Test Results after The First 30 Drops.

			board		component	
Leg #	timing	board side	ss	fail	ss	fail
L1	T0	A (face up)	4	0	60	0
		B (face down)	4	0	60	0
	HTS500	A (face up)	4	0	60	0
		B (face down)	4	0	60	0
	HTS1000	A (face up)	4	0	60	0
		B (face down)	4	3	60	4
L2	T0	A (face up)	4	0	60	0
		B (face down)	4	0	60	0
	HTS500	A (face up)	4	0	60	0
		B (face down)	4	0	60	0
	HTS1000	A (face up)	4	0	60	0
		B (face down)	4	4	60	10
L3	T0	A (face up)	4	0	60	0
		B (face down)	4	0	60	0
	HTS500	A (face up)	4	0	60	0
		B (face down)	4	0	60	0
	HTS1000	A (face up)	4	0	60	0
		B (face down)	4	3	60	3
L4	T0	A (face up)	4	0	60	0
		B (face down)	4	0	60	0
	HTS500	A (face up)	4	0	60	0
		B (face down)	4	0	60	0
	HTS1000	A (face up)	4	0	60	0
		B (face down)	4	0	60	0
L5	T0	A (face up)	4	0	60	0
		B (face down)	4	0	60	0
	HTS500	A (face up)	4	0	60	0
		B (face down)	4	0	60	0
	HTS1000	A (face up)	4	0	60	0
		B (face down)	4	0	60	0
L6	T0	A (face up)	4	0	60	0
		B (face down)	4	0	60	0
	HTS500	A (face up)	4	0	60	0
		B (face down)	4	0	60	0
	HTS1000	A (face up)	4	0	60	0
		B (face down)	4	0	60	0
L7	T0	B (face up)	4	0	60	0
		A (face down)	4	0	60	0
	HTS500	B (face up)	4	0	60	0
		A (face down)	4	0	60	0
	HTS1000	B (face up)	4	0	60	0
		A (face down)	4	3	60	4

5.3.2 RESULTS AFTER 1000 HOURS HTS

Drop test results after 1000 hours HTS are shown in Figure 19. Samples from Leg 2 (Sn/Ag/Cu ball and OSP finish) had the most failures for both number of failed boards and number of failed components. The number of components failed from Leg 2 was 2.9 times higher than that from Legs 1, 3, and 7 (all Sn/Ag/Cu ball and Ni/Au finish). Samples from Legs 1, 3, and 7 had similar failure rates. No components failed from the samples containing the Sn/Pb balls (Legs 4 - 6).

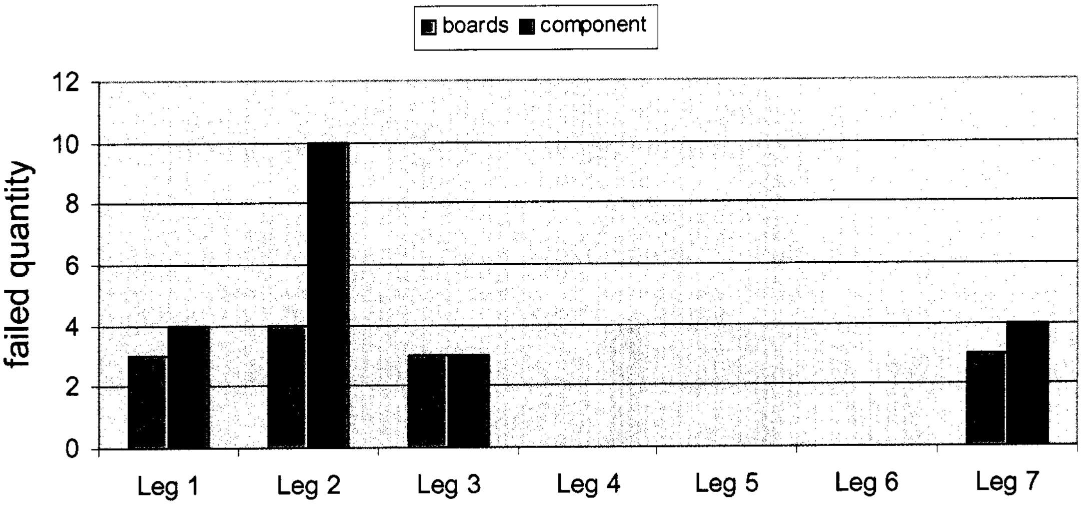


Figure 19. Drop test failure after 1000 hours HTS, face-down.

The location, on the board, where components failed, after 1000 hours HTS, is shown in Figure 20. Component locations and identification numbers are shown in Figure 21. Four components failed at location U2, 3 components at U4, and 2 components at U14. No components failed at U6, U7, U8, U10, U12, and U13 locations. The rest of the locations had one component failure each. There was no specific pattern in terms of failed component locations.

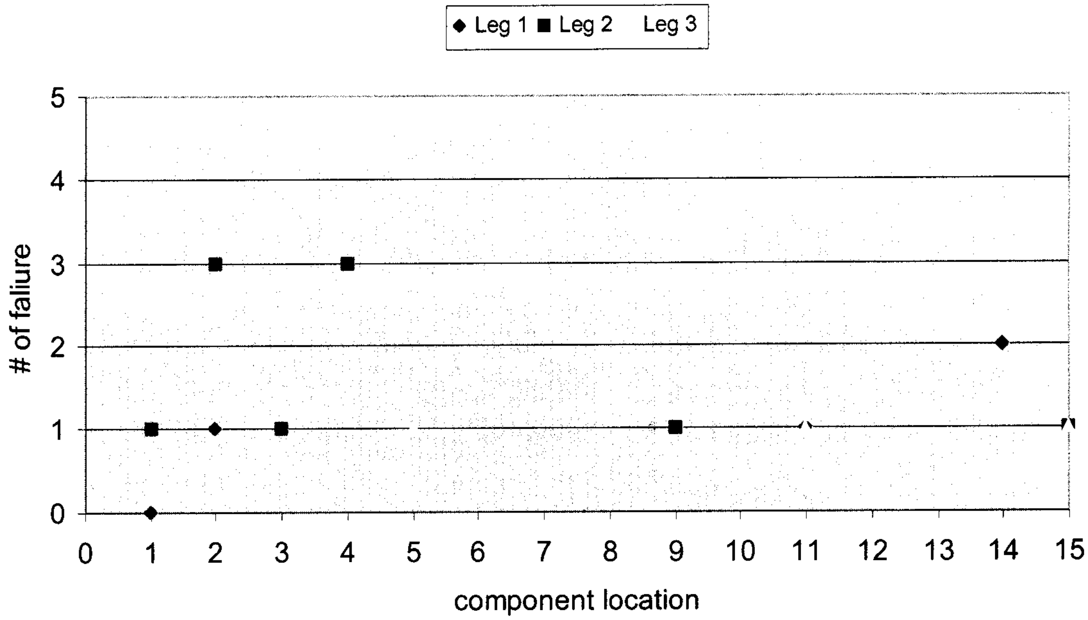


Figure 20. Failed component locations from 1000 hour HTS drop test.

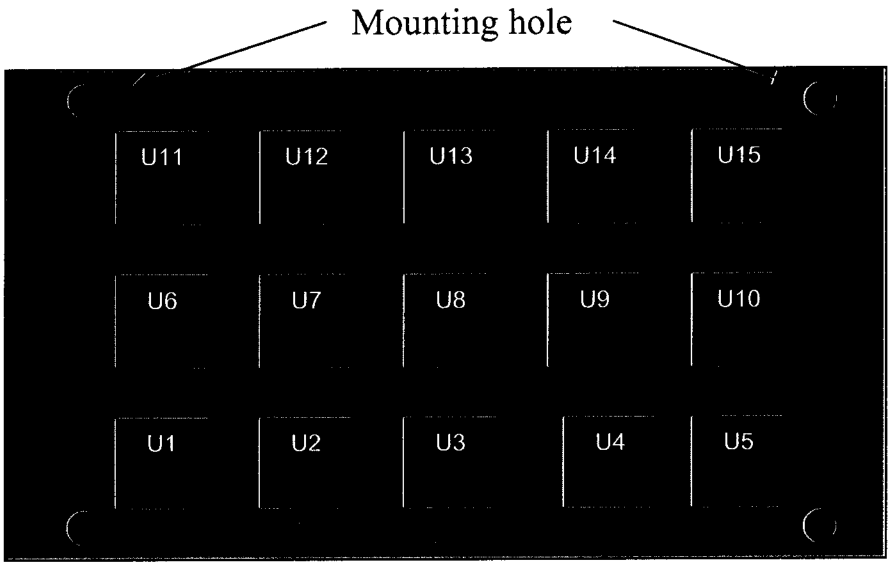


Figure 21. Component locations and identification numbers on a board.

The drop orientation of the via-in-pad side facing down or up did not make much difference in component failure rate or failed component locations when Leg 3 and Leg 7 results were compared. Leg 3 and Leg 7 have the same substrate finish of Ni/Au with no plating tails and the same solder ball (Sn/Ag/Cu) but the drop orientation was different. For Leg 3, a side with via-in-pad was face-up while the side with via-in-pad was face-down for Leg 7. A total of 3 boards and 3 components failed for Leg 3. 3 boards and 4 components failed for Leg 7.

5.3.3 RESULTS FROM 80% CUMULATIVE FAILURE TEST

One board from each leg was drop tested until 80% of the components on the board failed. Samples from Leg 4 and Leg 6 had the highest number of drops to 80% failure and Leg 2 samples had the lowest, as shown in Figure 22. Again, the Sn/Ag/Cu balls had a shorter drop test life than the Sn/Pb balls. Also, samples with the OSP finish (Leg 2, Leg 5) failed sooner than samples with the Ni/Au finish did.

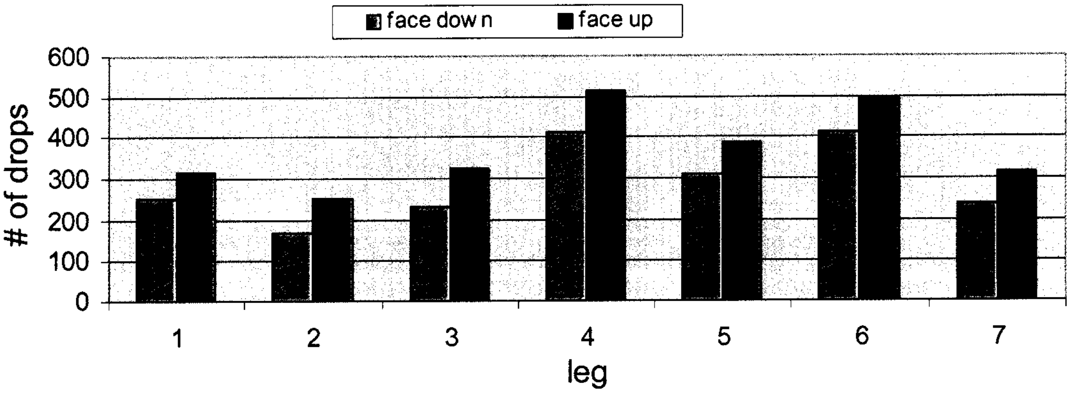


Figure 22. Average number of drops to 80% components failure, per leg.

In order to compare the number of drops to 80% failure, with statistical validity, between the Sn/Ag/Cu balls (Leg 1 – 3) and the Sn/Pb balls (Leg 4 – 6), a t-test was run for the components mounted on the face-down side as well as for the components mounted on the face-up side, as shown in Table 16.

Table 16. t-test Results.

Components mounted on face-down side

	Sn/Ag/Cu balls	Sn/Pb balls
Number of data points	36	36
Mean	218	366
95% confidence interval for Mean	187.5 ~ 247.5	335.6 ~ 395.6
Standard Deviation	67.1	109
Median	228	365

t = -6.96 s.d = 90.3 degrees of freedom = 70

P-value = 0.0001 $\alpha = 0.05$

Components mounted on face-up side

	Sn/Ag/Cu balls	Sn/Pb balls
Number of data points	36	36
Mean	296	464
95% confidence interval for Mean	266.2 ~ 325.5	434.5 ~ 493.8
Standard Deviation	66.7	107
Median	278	465

t = 8.00 s.d = 89.3 degrees of freedom = 70

P-value = 0.0001 $\alpha = 0.05$

The hypotheses were

$$H_o: \mu_1 = \mu_2, \quad H_1: \mu_1 \neq \mu_2.$$

As shown in Table 15, the P-value in both cases of the components mounted on the face-up side and the face-down side, was smaller than α. Therefore, the null hypothesis H_o: $\mu_1 = \mu_2$ was rejected. This means that the components with the Sn/Ag/Cu balls were significantly different, with 95% confidence, from the components with the Sn/Pb balls in terms of mean number of drops to 80% failure, whether the components were mounted on the face-up side or the face-down side.

The average number of drops required for 80% component failure by component location is shown in Figure 23. The components located at U8 (center of the board) had the lowest number of drops before 80% failure from both via-in-pad side and no via-in-pad side of the board. The components from U6, U10, U7, and U9 locations had the highest number of drops before 80% failure.

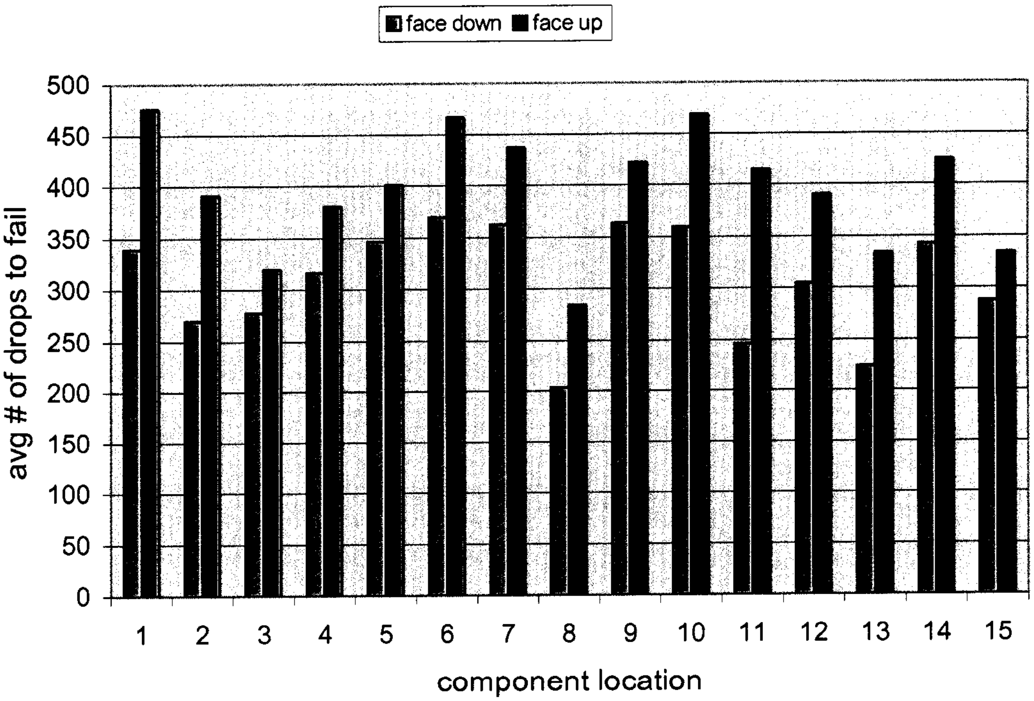


Figure 23. Average number of drops before 80% component failure, per component location.

Component locations versus number of drops to failure are plotted in Figure 24. Component locations where failure occurred before 200 drops were U8 with 4 failures, U11 with 3 failures, and U4, U12, U13 with 2 failures each. Based on Figures 23 and 24, location U8 was the worst spot in terms of number of drops to failure, followed by U13. The lowest number of drops to failure from the locations at U8 and U13 was expected as the solder ball joint stress during the board level drop test would be the highest at the center of the board, mounted with 4 screws to the drop test base plate. According to a simulation [11], components mounted at the board center have solder joint stress 5 times higher than components mounted on board corners and closest to mounting holes. However, the components at location U3 which was in line with the components at U8 and U13 did not show early failure, which was a surprise.

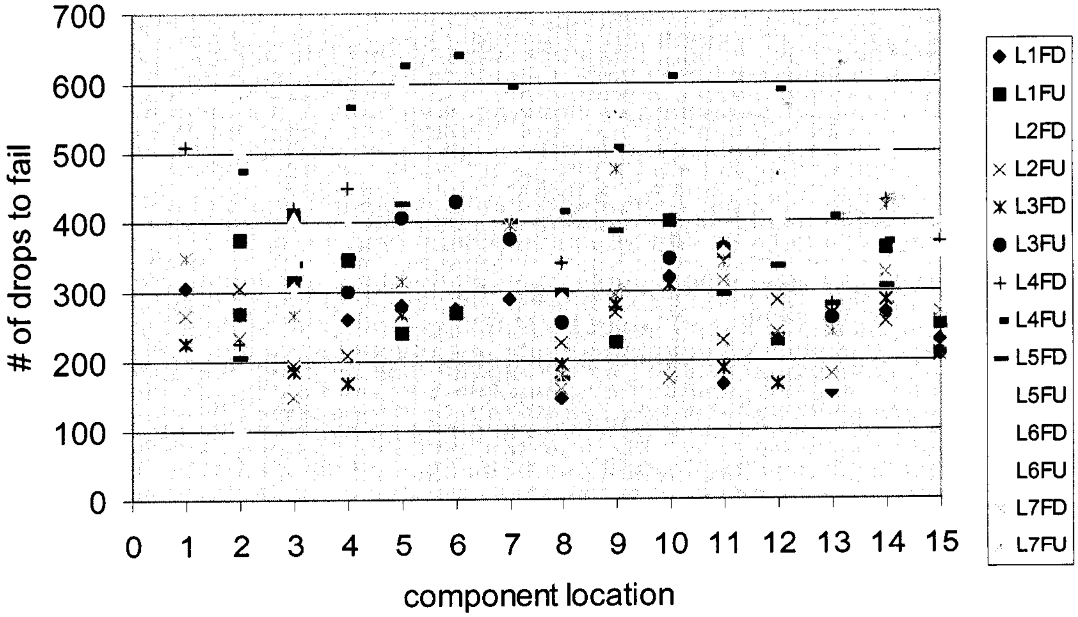


Figure 24. Component locations and number of drops to failure.

The number of drops to 80% component failure is shown in Figures 25 and 26 for the face-down side and the face-up side, respectively. As can be seen by comparing the data in both figures, the components mounted on the face-down side failed sooner than ones mounted on the face-up side. Leg 3 and Leg 7 had similar number of drops to 80% failure. Components containing Cu-OSP failed sooner than those containing Ni/Au.

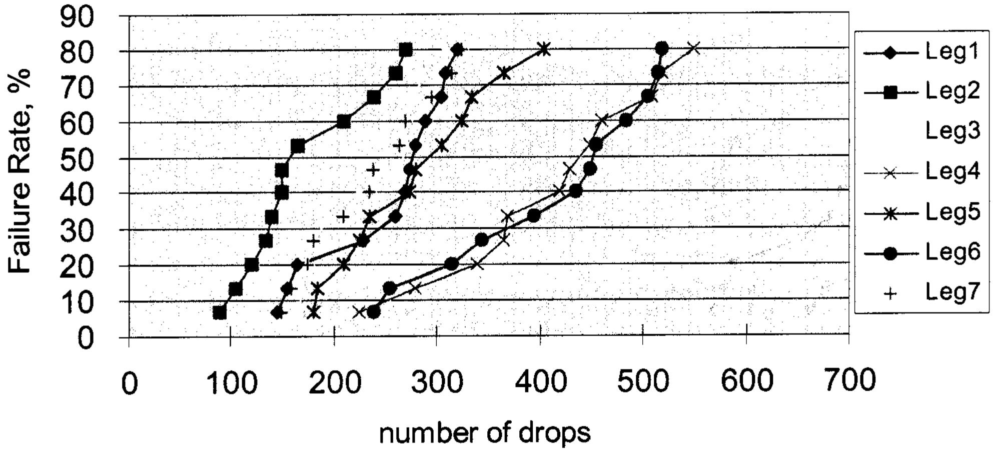


Figure 25. Number of drops to 80% failure for components on the face-down side.

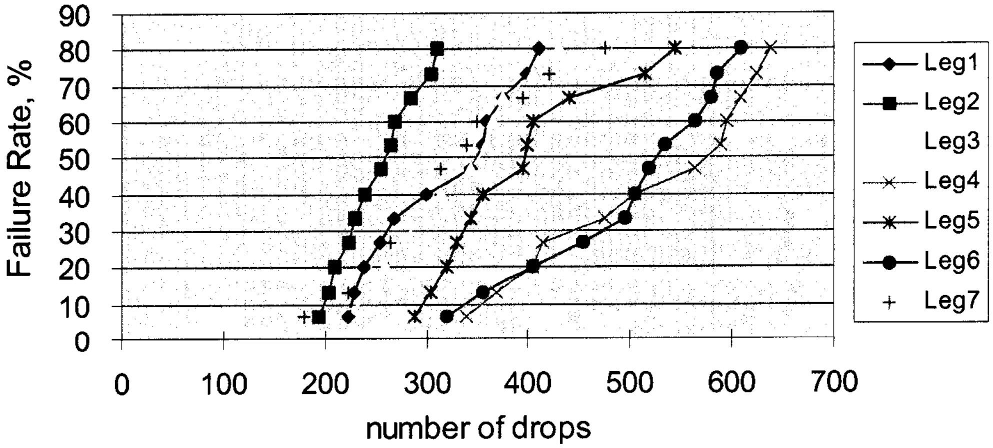
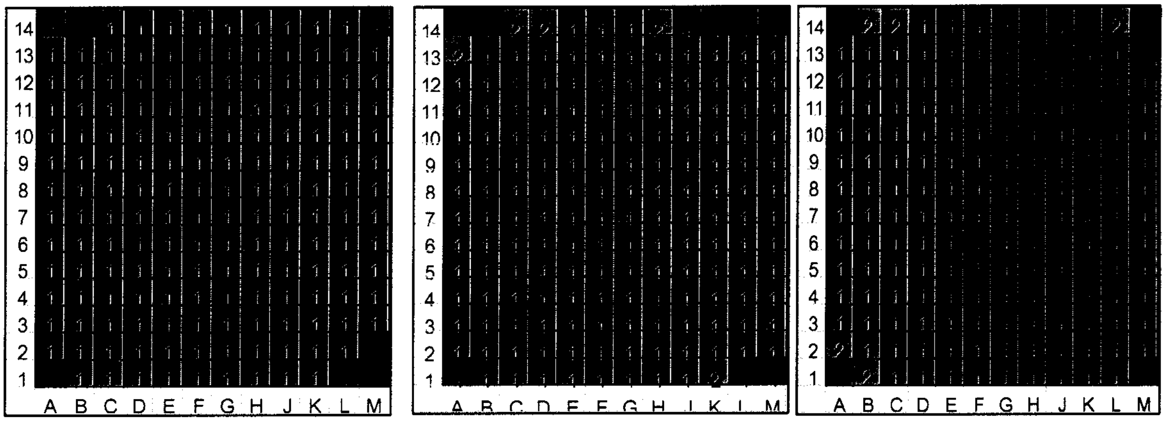


Figure 26. Number of drops to 80% failure for components on the face-up side.

5.4 FAILURE ANALYSIS

5.4.1 FA FOR COMPONENTS FAILED AFTER 1000 HOURS HTS

As shown previously in Figure 19, the Sn/Pb balls (Legs 4 – 6) had no failures after 1000 hours HTS while the Sn/Ag/Cu balls (Legs 1 – 3) failed. Three boards failed from Leg 1 and 3, respectively. All of the 4 boards in Leg 2 failed. All components that failed were from the face-down side. Dye and pry test results from Legs 1 - 3 are shown in Figure 27. The failure mode for each ball location is shown in each component ball map. As shown in Figure 27, all failures were on the substrate side based on failure modes, and the failed ball locations corresponded mostly to the component corners.



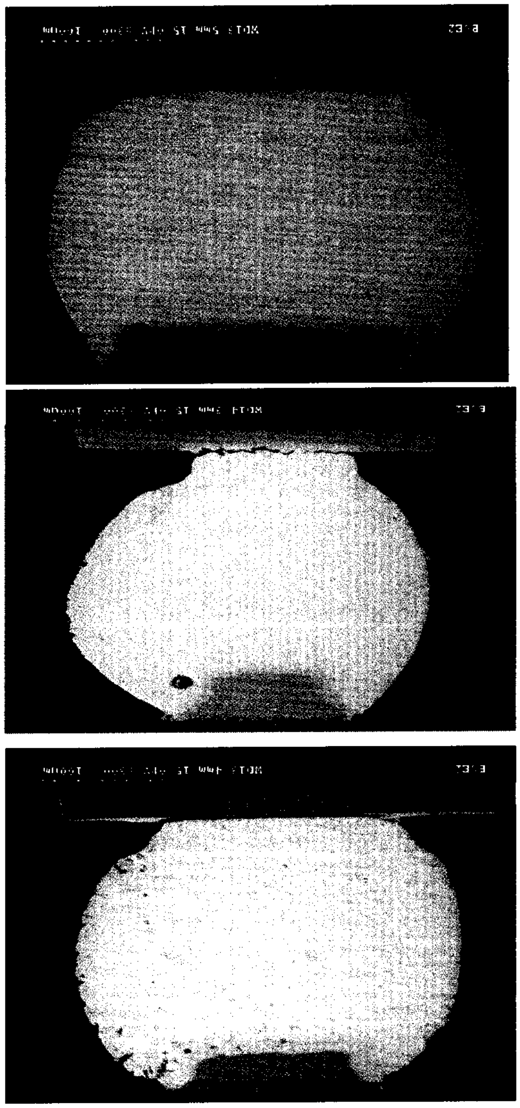
Leg 1
Board #1
Component #U16

Leg 2
Board #2
Component #U3

Leg 3
Board #1
Component #U5

Figure 27. Dye and pry test results after 1000 hours HTS.

Cross-sectional inspection was done for failed solder balls. As shown in Figure 28, the fracture surface was between the substrate pad and the solder ball, which suggests failure in or near the intermetallic compound (IMC) layers.



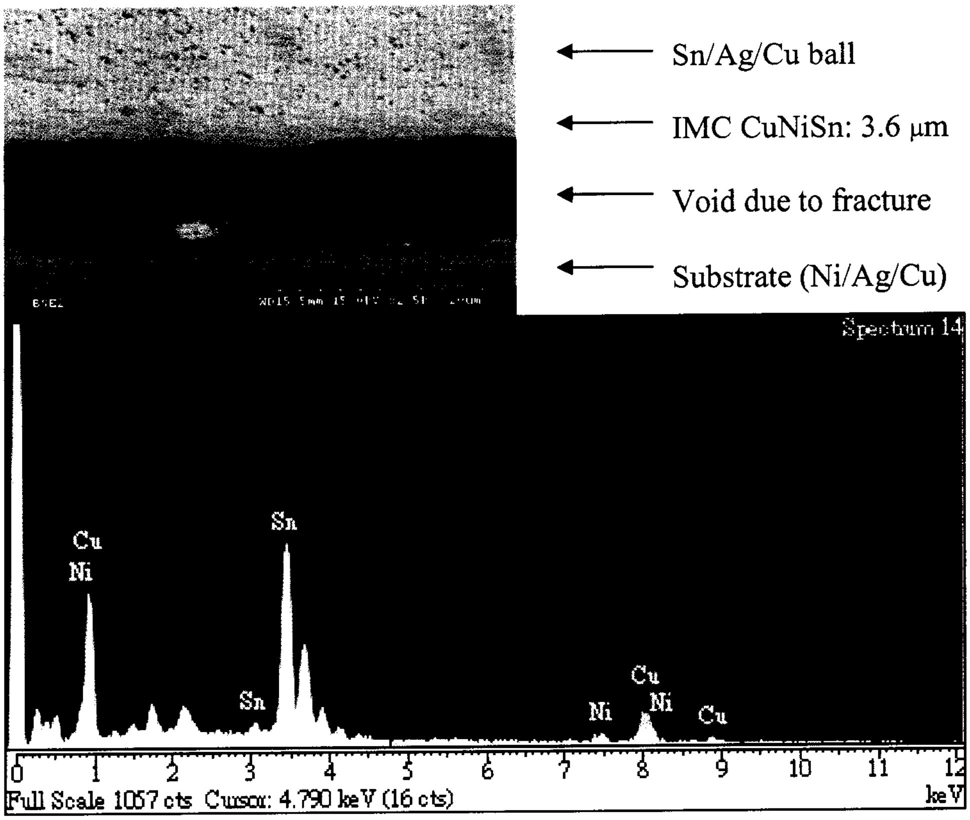
Leg 1, Sn/Ag/Cu ball, Ni/Au pad finish with plating tail, face-down

Leg 2, Sn/Ag/Cu ball, Cu-OSP pad finish with no plating tail, face-down

Leg 3, Sn/Ag/Cu ball, Ni/Au pad finish with no plating tail, face-down

Figure 28. Cross-section across failed balls after 1000 hours HTS.

For each cross-section, Energy Dispersive X-ray Spectroscopy (EDX) was done to identify the IMC material. The IMC thickness was also measured on a Scanning Electron Microscopy (SEM), as shown in Figures 29 through 31. There was fracture surface between the IMC and the Cu pad for the Ni/Au finish (Leg 1 and 3) while it was between the IMC and the Sn/Ag/Cu solder for the OSP finish (Leg 2). The IMC layer from the Leg 2 sample was about 3 μm thicker than that from the Legs 1 and 3. Also, Leg 2 sample had 2 layers of IMC.



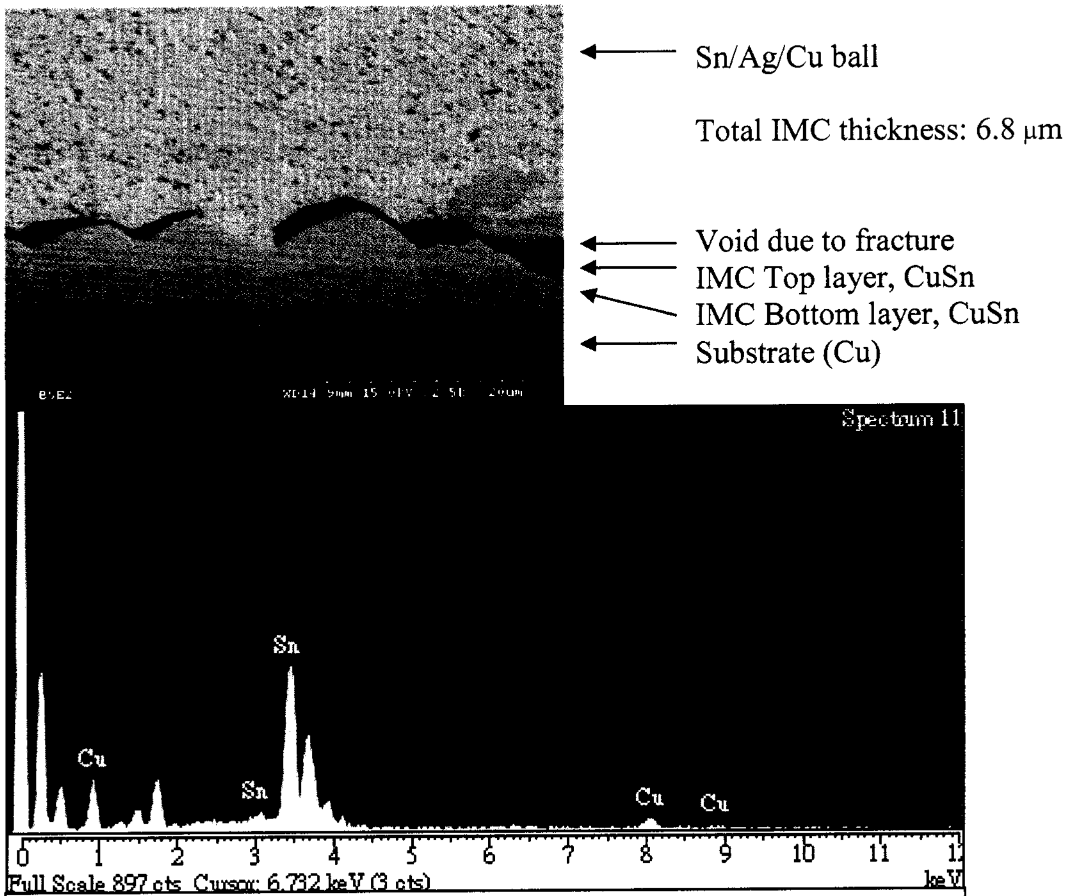
Sn/Ag/Cu ball

IMC CuNiSn: 3.6 μm

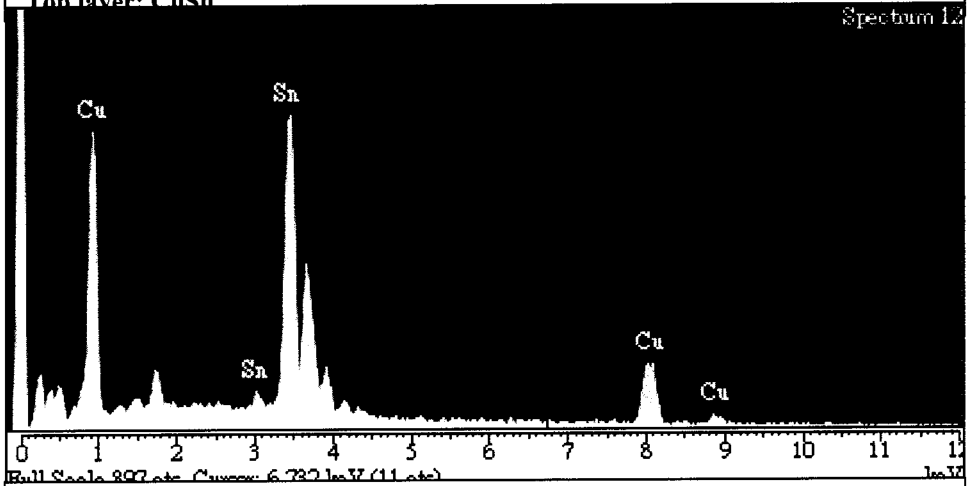
Void due to fracture

Substrate (Ni/Ag/Cu)

Figure 29. IMC layer and thickness after 1000 hours HTS, Leg 1, face-down.



Top layer: CuSn



Bottom layer: CuSn

Figure 30. IMC layers and thickness, after 1000 hours HTS, Leg 2, face-down.

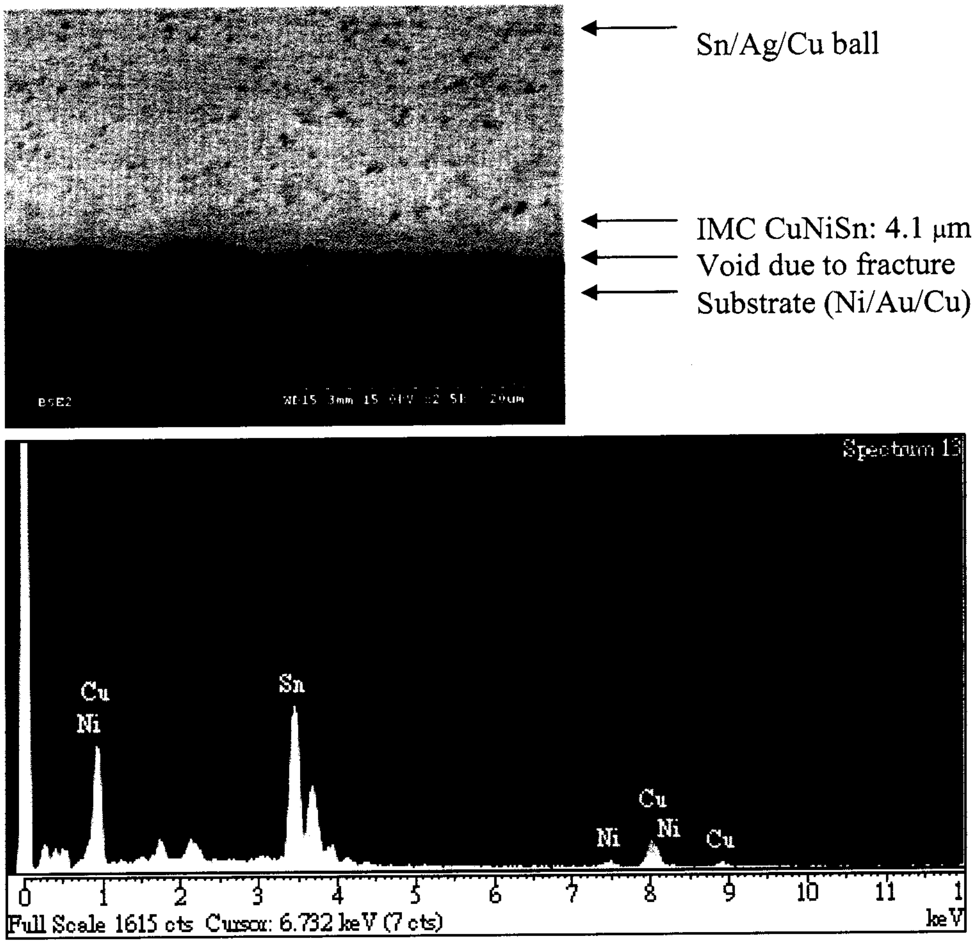
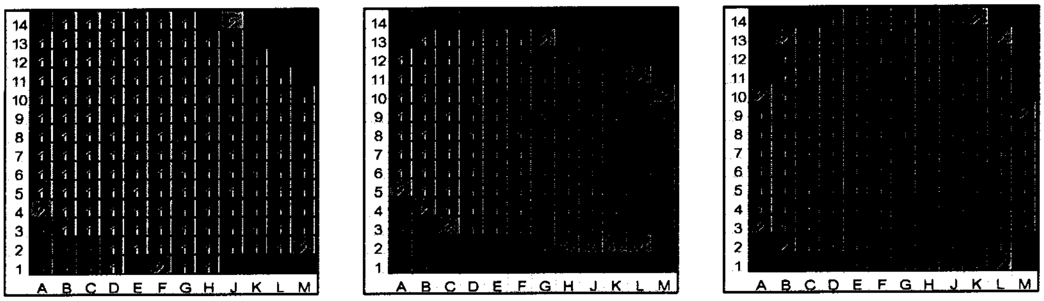


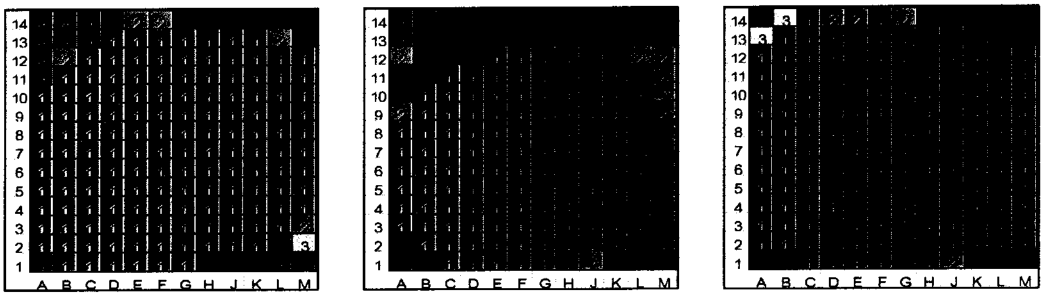
Figure 31. IMC layer and thickness, after 1000 hours HTS, Leg 3, face-down..

5.4.2 FA FOR COMPONENTS FAILED FROM 80% CUMULATIVE FAILURE TEST

Dye and pry test results for the components that failed from the 80% cumulative failure test are shown in Figures 32 and 33. All failures, except one from Leg 4, face-up which had one ball failed from the board side, were from the substrate side. The failed ball locations corresponded mostly to the component corners, whether the components were mounted on the face-up side or on the face-down side. The total number of balls that failed on the face-up side and the face-down side are summarized in Figure 34. The total number of balls that failed in Mode 4 (red dye covering more than 90% up to 100% substrate pad) and Mode 2 (red dye covering less than 10% of substrate pad) are summarized in Figure 35. As can be seen in Figures 34 and 35, a higher number of balls from the face-down side failed than that from the face-up side. Components from Leg 2 (Sn/Ag/Cu ball, Cu-OSP pad finish) had the highest total number of balls failed and the highest number of Mode 4 failure balls. The number of Mode 4 failure balls out of the total number of balls that failed was 79% for the Sn/Ag/Cu balls and 55% for the Sn/Pb balls.

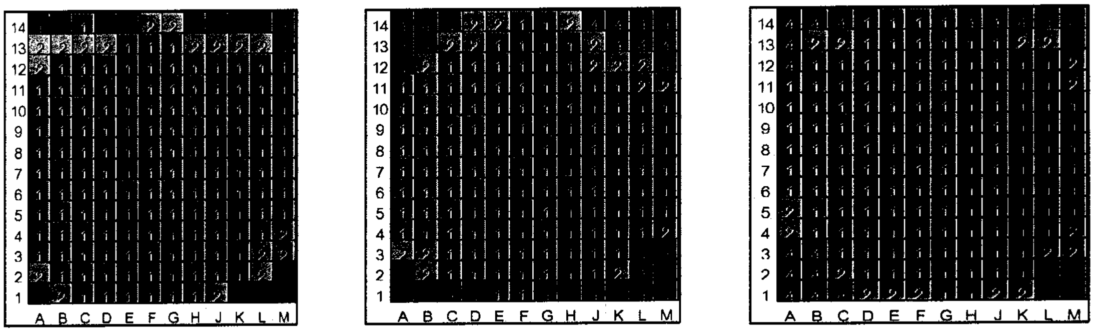


Leg 1, board #1, U8 Leg 2, board #1, U11 Leg 3, board #1, U12 Face-down

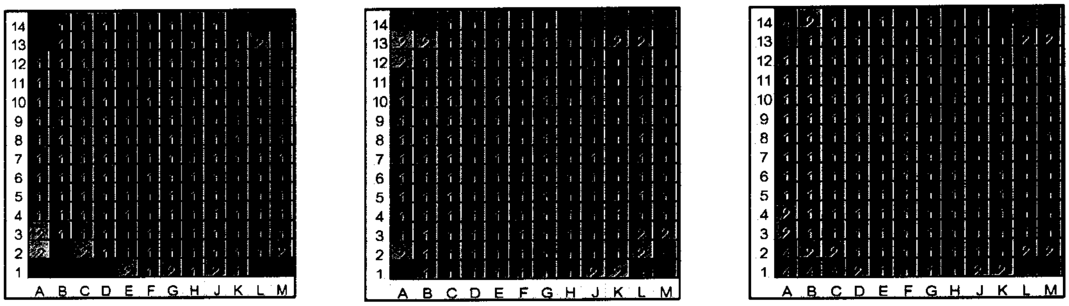


Leg 1, board #1, U12 Leg 2, board #1, U15 Leg 3, board #1, U10 Face-up

Figure 32. Dye and pry test results from zero-hour 80% failure test, Legs 1 – 3.



Leg 4, board #1, U15 Leg 5, board #1, U8 Leg 6, board #1, U11 Face-down



Leg 4, board #1, U9 Leg 5, board #1, U12 Leg 6, board #1, U9 Face-up

Figure 33. Dye and pry test results from zero-hour 80% failure test, Legs 4 – 6.

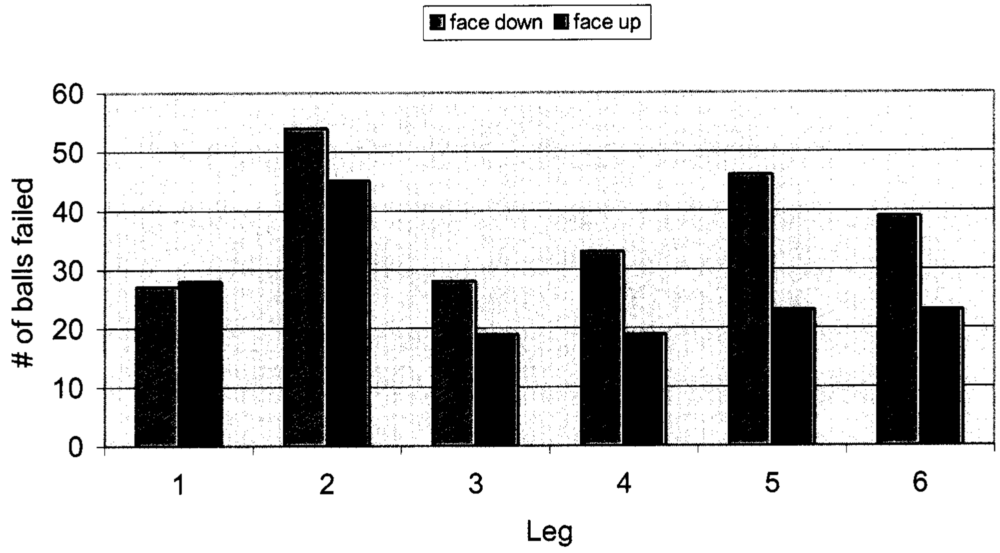


Figure 34. Total number of balls, face-up and face-down.

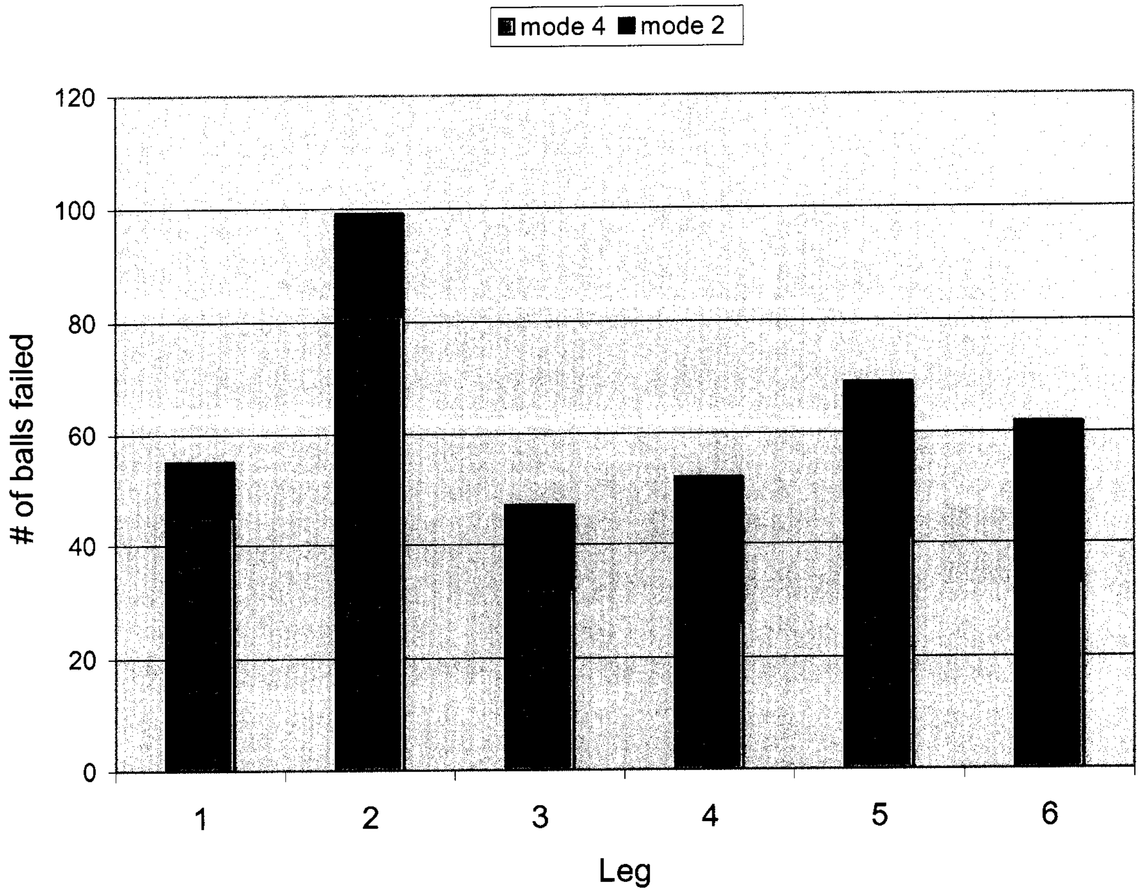


Figure 35. Total number of balls failed in Modes 2 and 4.

Cross-sectional inspection was done for each leg and for both the face-down side and the face-up side, as shown in Figures 36 through 39. All failures for the Sn/Ag/Cu balls and the Sn/Pb balls were on the substrate side. However, the failure was between the ball pad and the solder ball for the Sn/Ag/Cu balls (Legs 1 – 3) while it was within the solder ball itself for the Sn/Pb balls (Legs 4 – 6).

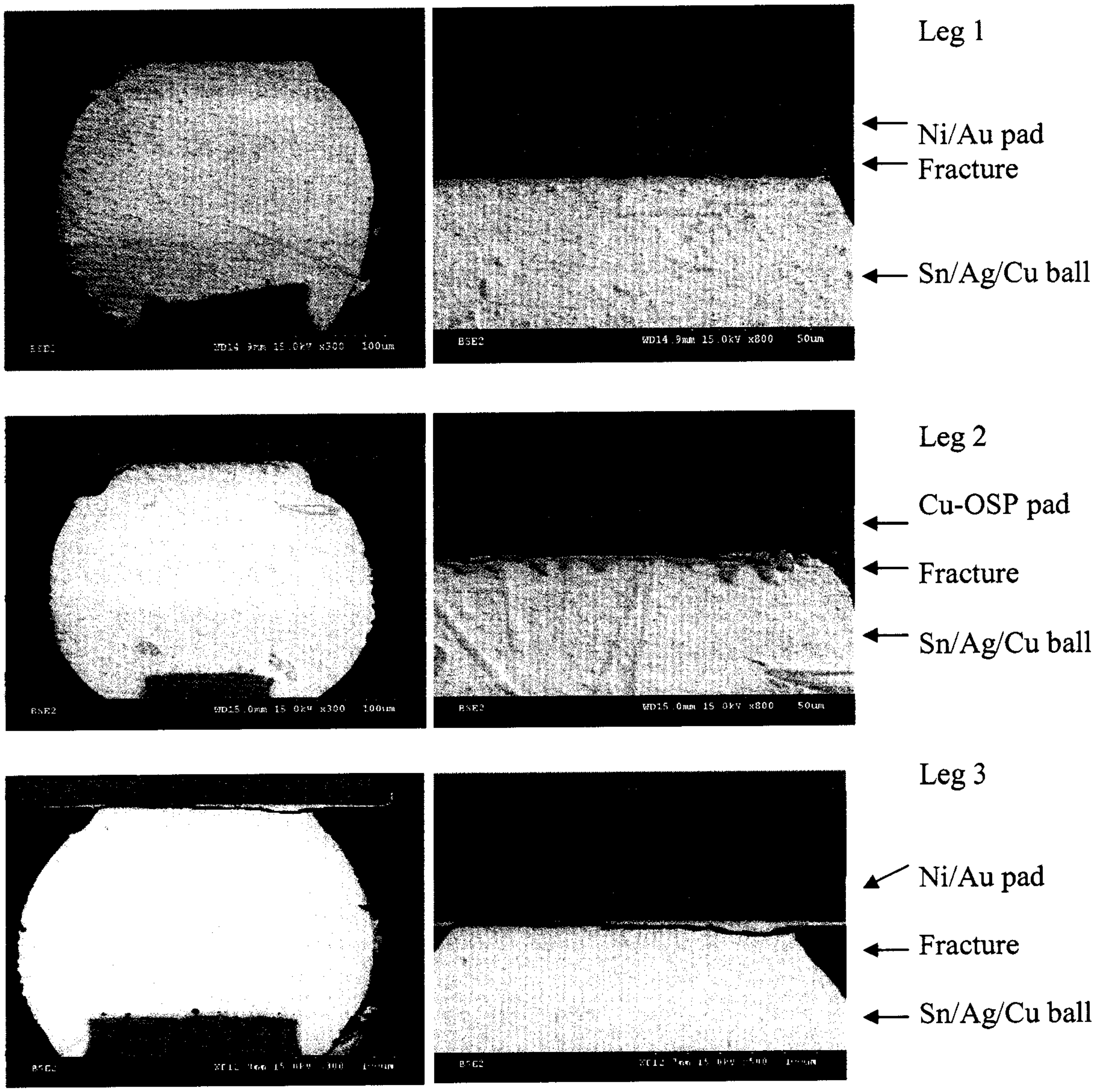


Figure 36. Cross-sections of failed solder balls after 80% cumulative failure test on zero-hour boards, face-down, Legs 1 – 3.

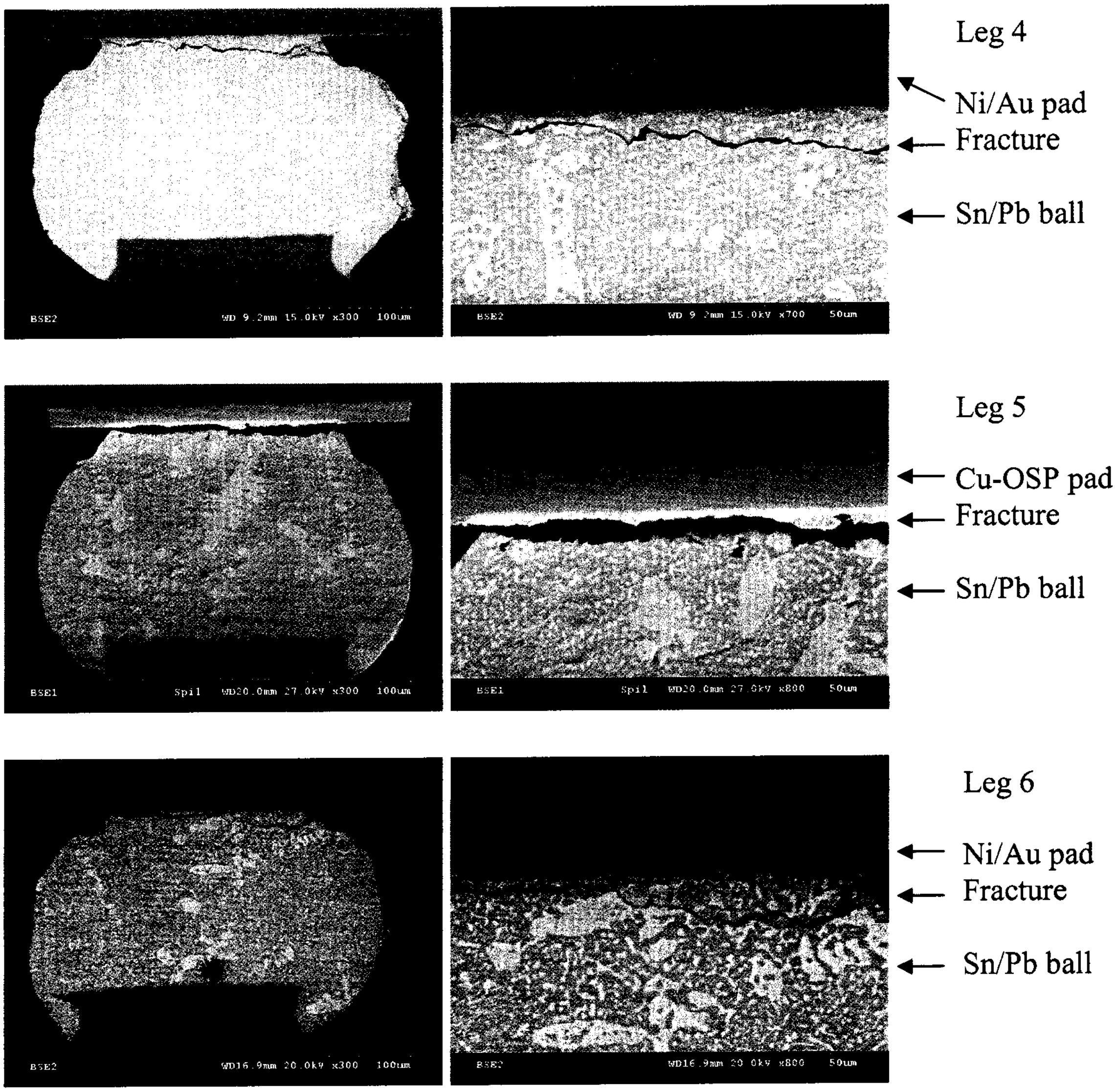


Figure 37. Cross-sections of failed solder balls after 80% cumulative failure test on zero-hour boards, face-down, Legs 4 - 6.

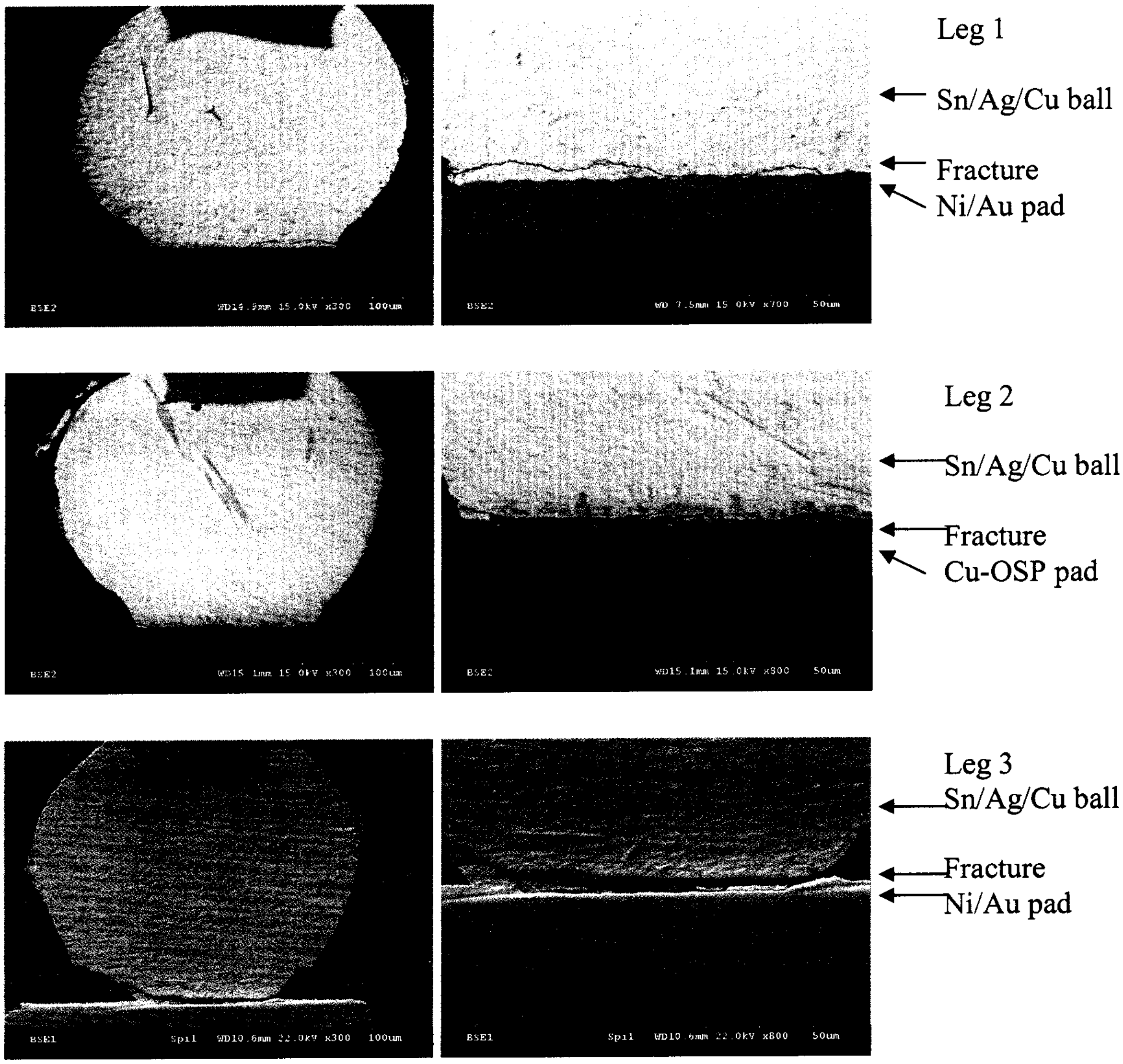


Figure 38. Cross-sections of failed solder balls after 80% cumulative failure test on zero-hour boards, face-up, Legs 1 – 3.

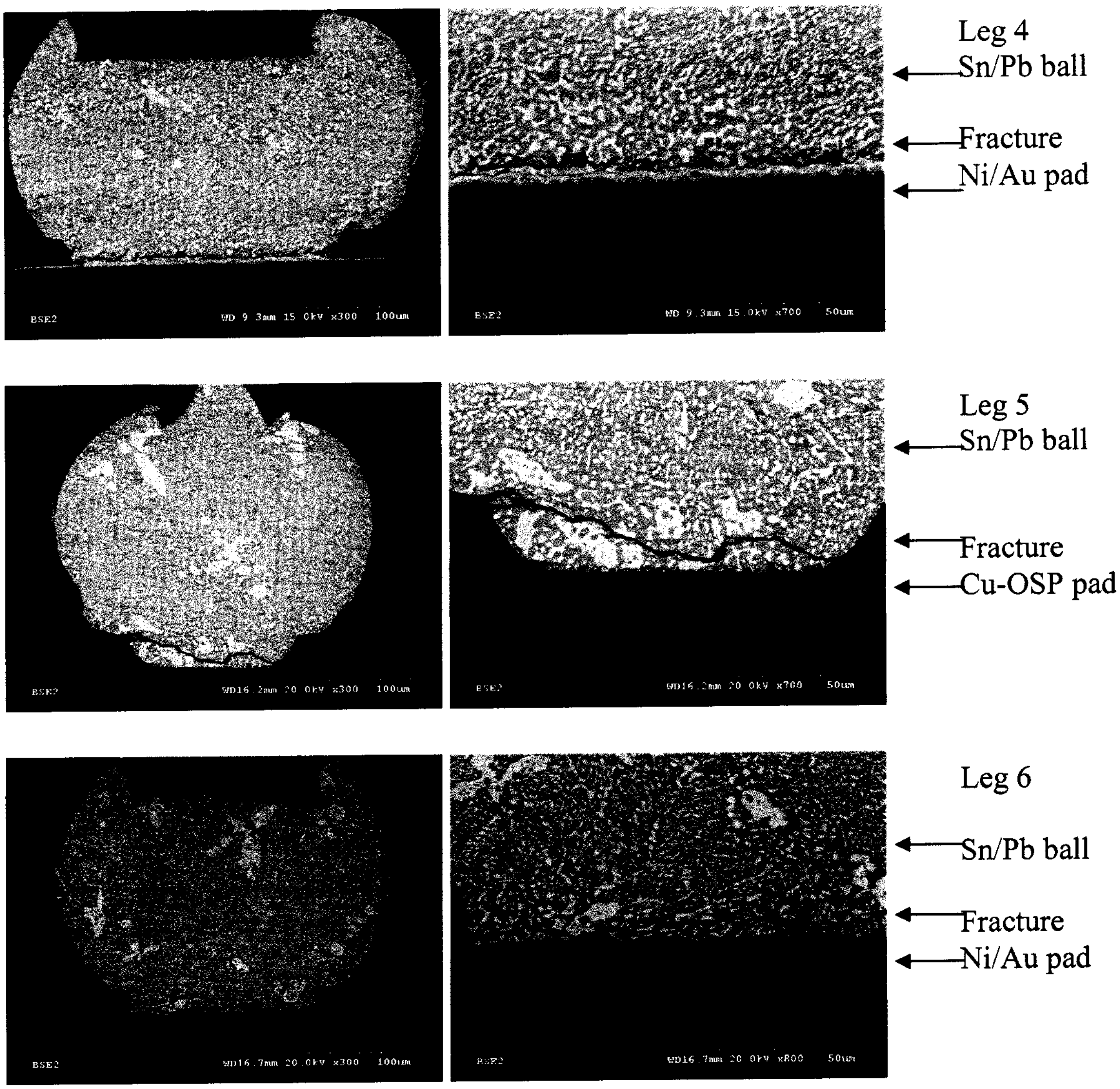
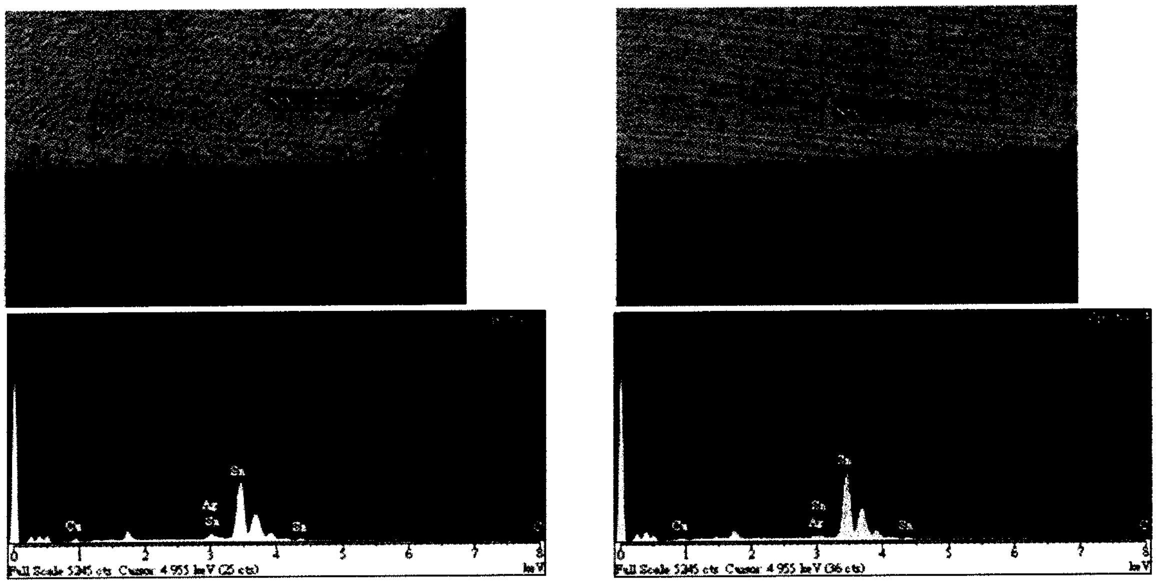


Figure 39. Cross-sections of failed solder balls after 80% cumulative failure test on zero-hour boards, face-up, Legs 4 - 6.

An EDX analysis was done on one sample of Leg 2 (Sn/Ag/Cu solder ball plus Cu-OSP pad finish) and Leg 3 (Sn/Ag/Cu solder ball plus Ni/Au pad finish) to compare the Cu content in the solder joints in an effort to understand why the components with the Cu-OSP pad finish failed earlier than the components with the Ni/Au pad finish. As can be seen in Figure 40, there was no noticeable difference in the Cu content from both samples. So, the question about the components with the Cu-OSP pad finish having a short drop cycle life remained unanswered.



Leg 2 Sn: 94.03 weight %
Ag: 3.33
Cu: 2.63

Leg 3 Sn: 95.09 weight %
Ag: 2.20
Cu: 2.72

Figure 40. EDX on Leg 2 and 3 samples after 80% cumulative failure test on zero-hour boards.

The solder ball stand-off height was measured from the cross-sectioned samples and the results are summarized in Table 17. The average stand-off height of the Sn/Ag/Cu balls (Legs 1 – 3, Leg 7) was about 9% (16 μm) higher than that of the Sn/Pb balls (Legs 4 – 6) - 197 μm versus 181 μm. The difference in the stand-off height might be caused by the different reflow profiles used for each solder ball material. The components mounted on the face-up side of the board had a slightly higher stand-off than the components mounted on the face-down side - 199 μm versus 195 μm for Sn/Ag/Cu balls and 182 μm versus 180 μm for Sn/Pb balls.

Table 17. Solder Ball Stand-off Height, Unit: μm.

	Leg 1	Leg 2	Leg 3	Leg 4	Leg 5	Leg 6	Leg 7
Face-down	200	188	200	171	181	182	192
	192	189	200	175	180	185	198
	194	196	201	180	175	186	189
	192	193	197	175	182	179	196
	190	191	198	178	181	185	197
average	194	192	199	176	180	184	195
Face-up	195	201	199	184	182	177	195
	196	200	198	183	186	181	196
	203	198	203	180	184	180	195
	198	196	200	188	177	184	192
	205	197	199	181	180	184	199
average	199	198	200	183	182	182	196

5.5 DISCUSSION OF RESULTS

The components with the Sn/Pb balls had about 1.6 times higher number of drops before 80% component failure than the components with the Sn/Ag/Cu balls. As can be seen in Table 16 of the t-test summary, the average number of drops before 80% component failure was 366 drops for the Sn/Pb balls and 218 drops for the Sn/Ag/Cu balls for the components mounted on the face-down side, and 464 drops for the Sn/Pb balls and 296 drops for the Sn/Ag/Cu balls for the components mounted on the face-up side of the board. One of the characteristics of the drop test is a high strain rate caused by an impact pulse. Since the high strain rate would not allow enough time for the solder to deform, the drop test easily shows the characteristics of interface bonding, especially for a high strength solder such as Sn/Ag4%/Cu0.5% for which the elastic modulus is about 1.4 times higher than that of Sn63%/Pb37% [16]. The ball shear force of the Sn/Ag4%/Cu0.5% balls was 1.25 times higher than that of the Sn63%/Pb37% balls. This explains why the fracture surface was along with the IMC layers for the Sn/Ag4%/Cu0.5% balls (Legs 1 – 3) while it was within the solder ball itself for the Sn63%/Pb37% balls (Legs 4 – 6).

For the components that failed after 1000 hours HTS, the fracture surface was between the NiCuSn IMC and the Cu pad for the Ni/Au finish (Legs 1 and 3), which means that the interface bonding between the NiCuSn IMC and the solder is stronger than that between the NiCuSn IMC and the Cu pad. For the Cu-OSP finish (Leg 2), the fracture surface was between the CuSn IMC and the solder ball, which means that the interface bonding between the CuSn IMC and the Cu pad is stronger than that between the CuSn IMC and the solder ball. The same Sn/Ag/Cu solder balls were used for all of Legs 1 -3. The IMC from Leg 2 was also about 3 μm thicker than that from Legs 1 and 3. Balls with the Cu-OSP pad finish had the lowest shear force and the highest thermal degradation among the Sn/Ag/Cu balls even though the Sn/Pb balls did not show much difference in shear force and thermal degradation among the 3 pad finishes. The IMC thickness for the Cu-OSP pad finish plus Sn/Ag/Cu ball after 1000 hours HTS was almost 2 times thicker than that for the Ni/Au pad finish plus Sn/Ag/Cu. It was not clear why the components with the Cu-OSP pad finish had about a 30% shorter drop cycle life, when tested at zero hour, than those with the Ni/Au pad finish. The components with the Cu-OSP pad finish had 2.9 times more number of components failed after HTS 1000 hours than those with the Ni/Au. The components with the Cu-OSP pad finish had 1.9 times more number of balls failed in Mode 4 (red dye covering more than 90% of substrate pad area) after HTS 1000 hours than those with the Ni/Au for the Sn/Ag/Cu balls and had 1.2 times more number of balls failed in Mode 4 for the Sn/Pb balls.

There was no statistically significant difference between the substrates with plating tails and the substrates without plating tails in terms of number of drops to failure, bond pull strength, and solder ball shear strength. Since the concern is the cleanliness of wire bonding pads and solder ball pads after chemical etching and cleaning during substrate manufacturing process, the impact from having no plating tail process will be dependent upon how well the cleaning after the etching process is controlled.

During the drop test, a compression load was applied to the solder balls on the face-up side by the impact pulse while a tensile load was applied to the solder balls on the face-down side. The tensile load caused the components mounted on bottom side of the board to fail sooner than the components mounted on the top side. The components located at U8 failed first on both the face-up and the face-down sides. U8 is located at the center of the board and is farthest away from four mounting screws. As can be seen in the drop test results for Legs 3 and 7, the board design of via-in-pad versus no via-in-pad did not make any difference to drop test performance. It is because the difference in the pad design was too small to change the pad surface area or Cu thickness on the pads.

All the balls that failed, except for one, failed at the substrate side. The reason why the balls failed mostly on the substrate side is because the ball pad design was solder-mask-defined (SMD) for the substrate and non-solder-mask-defined (NSMD) for the boards. The NSMD pad provides more surface contact area for the solder ball and a locking mechanism by the exposed pad side walls. So, the solder ball bonding force to the board is higher than that to the substrate.

5.6 SUMMARY

The effect of solder ball material and its ball pad finish on CSP package drop test performance was examined in this study. The combinations of Sn/Ag4%/Cu0.5% and Sn63%/Pb37% solder balls, with 3 different ball pad finishes of Ni/Au with plating tails, Ni/Au without plating tails, and Cu-OSP (organic solderability preserve) without plating tails were tested according to the industry standard of JEDEC test method JESD22-B111, using 10 x 10 x 1.2 mm CSP packages with 168 balls per package. The components with the Sn/Pb balls had much longer drop cycle life than the components with the Sn/Ag/Cu balls. The components with the Ni/Au pad finish had higher number of drops to failure than the components with the Cu-OSP finish had. Plating tail and no-plating tail did not make a significant difference in terms of number of drops to failure, bond pull force, and solder ball shear force. It was determined that the combination for the best drop test performance is Sn63%/Pb37% ball plus Ni/Au pad finish.

6 CONCLUSIONS

The results of this study demonstrated that the CSP's drop test performance was a function of solder ball material and ball pad finish, and that the number of drops before failure was different for each solder ball-pad finish combination. The components with the Sn/Pb balls had about 1.6 times higher number of drops before 80% component failure than the components with the Sn/Ag/Cu balls. The fracture surface was along with the IMC layers for the Sn/Ag4%/Cu0.5% balls while it was within the solder ball itself for the Sn63%/Pb37% balls. The components with the Cu-OSP pad finish had about a 30% shorter drop cycle life, when tested at zero hour, than those with the Ni/Au pad finish. There was no statistically significant difference between the substrates with plating tails and the substrates without plating tails in terms of number of drops to failure, bond pull strength, and solder ball shear strength. The board design of via-in-pad versus no via-in-pad did not make any difference to drop test performance.

During this study, it was not clear why the components with the Cu-OSP pad finish had about a 30% shorter drop cycle life, when tested at zero hour, than those with the Ni/Au pad finish. Further studies are recommended to investigate the reason why the components with the Cu-OSP pad finish had shorter drop cycle life, and to compare CSP component drop test performance between the substrates with Cu-OSP pad finish and the substrates with other common pad finishes such as solder-on-pad (SOP), immersion Ag, and direct Au. Also, recommended is to evaluate board level drop test performance for other leading Pb-free solder ball materials such as Sn96.5%/Ag3.5% and Sn/Cu0.75%.

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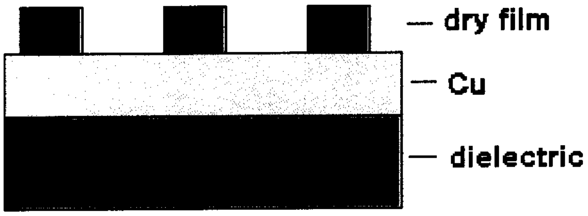
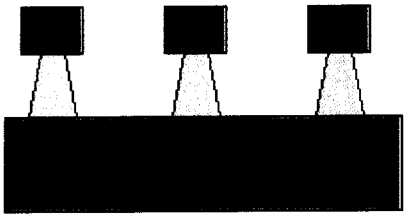
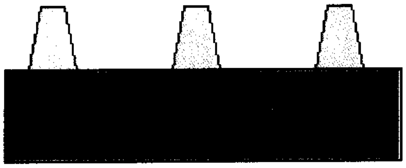
Appendix A. Substrate Manufacturing Flow; with Plating Tails



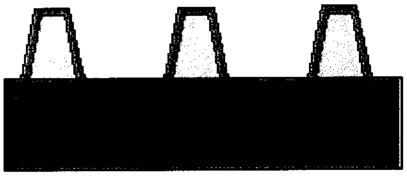
1. After core and prepreg layers are laminated, via holes are mechanically drilled and plated with Cu, a dry film is placed on top of plated Cu plane.



2. Cu exposed outside dry film is etched away, by forming trace lines. Plating tails are still attached to the trace lines.

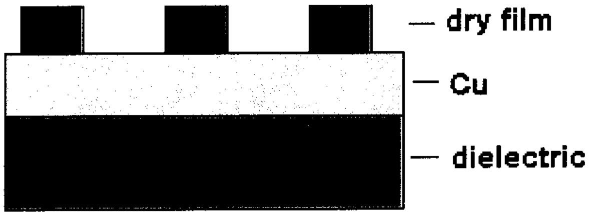


3. Dry film is peeled off.

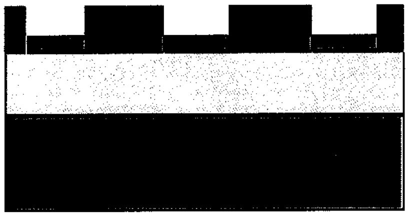


4. Ni is plated over Cu and then Au is plated. This is an electrolytic plating so the plating tails provide electrical connections to all traces throughout the substrate panel. The plating is the last step in the process so the plated gold surface is clean. This process is the least expensive. However, as all traces are still connected together through the plating tails, electrical continuity tests cannot be done on the bare substrates. The plating tails are disconnected later when individual substrates are singulated from the strip or matrix at the end of IC assembly.

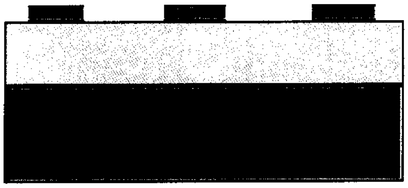
Appendix B. Substrate Manufacturing Flow; with No Plating Tails



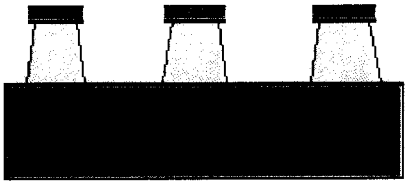
1. After core and prepreg layers are laminated, via holes are mechanically drilled and plated with Cu, a dry film is placed on top of plated Cu plane.



2. Ni/Au plating is done on Cu plane exposed by the dry film.



3. Dry film is peeled off.



4. Cu exposed outside Au plated areas is etched away, by forming trace lines without leaving any plating tails. An electrical continuity test can be done on individual traces since they are all isolated from each other. However, this process is more expensive than the process with plating tails. Since a chemical etching is done after Au plating, Au plated surface may be contaminated.

Appendix C. Wire pull test results at zero hour bake at 150°C.

		zero hour @ 150°C					
		Leg 1		**Leg 2**		**Leg 3**	
Pkg	wire #	**gram**	**mode**	**gram**	**mode**	**gram**	**mode**
SN1	1	5.17	E	6.55	E	6.38	E
	2	5.47	E	5.28	E	5.18	E
	3	5.36	E	6.45	E	7.04	E
	4	4.99	E	6.23	E	6.06	E
	5	6.32	E	6.86	E	5.89	E
SN2	1	6.36	E	6.46	E	6.64	E
	2	6.09	E	6.72	E	6.83	E
	3	6.17	E	6.16	E	6.46	E
	4	5.88	E	6.76	E	6.35	E
	5	6.56	E	6.53	E	6.42	E
SN3	1	6.95	E	6.8	E	6.58	E
	2	7.36	E	7.59	E	5.88	E
	3	6.6	E	5.23	E	5.76	E
	4	5.28	E	6.35	E	5.85	E
	5	6.23	E	5.91	E	6.12	E
SN4	1	7.05	E	6.21	E	6.23	E
	2	6.96	E	6.5	E	7.44	E
	3	6.56	E	5.6	E	6.33	E
	4	6.58	E	6.23	E	6.5	E
	5	6.01	E	6.12	E	6.56	E
SN5	1	5.76	E	6.57	E	6.01	E
	2	6.53	E	6.37	E	6.39	E
	3	6.82	E	6.85	E	6.75	E
	4	6.33	E	6.35	E	6.32	E
	5	6.68	E	6.55	E	6.28	E

Appendix D. Wire pull test results after 48 hours at 150°C bake.

		48 hours @ 150°C					
		Leg 1		**Leg 2**		**Leg 3**	
Pkg	wire #	**gram**	**mode**	**gram**	**mode**	**gram**	**mode**
SN1	1	6.68	E	6.25	E	6.29	E
	2	6.48	E	6.15	E	6.6	E
	3	7.13	E	6.28	E	6.16	E
	4	5.84	E	6.5	E	6.09	E
	5	6.82	E	5.97	E	5.66	E
SN2	1	6.17	E	6.22	E	6.92	E
	2	5.75	E	6.57	E	7.16	E
	3	6.65	E	6.33	E	6.18	E
	4	6.19	E	6.18	E	7.16	E
	5	5.78	E	5.35	E	6.07	E
SN3	1	5.32	E	6.62	E	6.54	E
	2	5.64	E	5.89	E	5.98	E
	3	7.56	E	6.22	E	7.12	E
	4	7.39	E	5.15	E	5.86	E
	5	6.6	E	6.36	E	6.35	E
SN4	1	6.64	E	6.36	E	7.66	E
	2	5.58	E	6.58	E	6.98	E
	3	5.02	E	5.98	E	5.74	E
	4	6.77	E	6.45	E	5.32	E
	5	6.13	E	6.1	E	6.39	E
SN5	1	6.99	E	7.39	E	6.12	E
	2	6.82	E	6.68	E	6.62	E
	3	7.26	E	6.23	E	5.73	E
	4	6.58	E	5.99	E	6.01	E
	5	5.8	E	6.34	E	5.98	E

Appendix E. Wire pull test results after 96 hours at 150°C bake.

		96 hours @ 150°C					
		Leg 1		**Leg 2**		**Leg 3**	
Pkg	wire #	**gram**	**mode**	**gram**	**mode**	**gram**	**mode**
SN1	1	6.09	E	6.19	E	6.13	E
	2	6.4	E	5.73	E	6.04	E
	3	6.56	E	5.16	E	5.35	E
	4	5.89	E	5.09	E	7.06	E
	5	5.46	E	5.56	E	6.14	E
SN2	1	6.82	E	6.3	E	6.23	E
	2	5.76	E	6.46	E	5.29	E
	3	5.98	E	6.08	E	5.38	E
	4	5.36	E	5.96	E	6.22	E
	5	5.87	E	5.97	E	5.39	E
SN3	1	6.34	E	6.44	E	5.98	E
	2	5.78	E	5.52	E	5.42	E
	3	6.02	E	5.62	E	6.04	E
	4	6.62	E	5.76	E	6.6	E
	5	6.01	E	6.25	E	6.5	E
SN4	1	5.3	E	6.6	E	5.37	E
	2	5.41	E	5.98	E	6.55	E
	3	5.4	E	5.04	E	6.15	E
	4	5.35	E	6.1	E	6.04	E
	5	6.13	E	6.12	E	6.59	E
SN5	1	5.52	E	5.98	E	5.39	E
	2	5.32	E	5.84	E	6.02	E
	3	6.26	E	5.12	E	6.06	E
	4	6.21	E	6.78	E	6.42	E
	5	5.76	E	6.08	E	5.98	E

Appendix F. Wire pull test results after 192 hours at 150°C bake.

		192 hours @ 150°C					
		Leg 1		**Leg 2**		**Leg 3**	
Pkg	wire #	**gram**	**mode**	**gram**	**mode**	**gram**	**mode**
SN1	1	5.8	E	6.62	E	5.69	E
	2	6.06	E	5.25	E	5.84	E
	3	6.49	E	4.73	E	6.2	E
	4	6.63	E	4.81	E	6.32	E
	5	6.46	E	6.79	E	6.49	E
SN2	1	5.45	E	6.97	E	6.15	E
	2	5.19	E	5.33	E	5.75	E
	3	5.7	E	4.96	E	5.64	E
	4	5.34	E	6.02	E	6.21	E
	5	6.19	E	5.46	E	6.59	E
SN3	1	6.47	E	5.41	E	5.22	E
	2	6.42	E	5.29	E	6.29	E
	3	6.45	E	5.44	E	5.75	E
	4	5.35	E	5.8	E	6.29	E
	5	5.81	E	5.92	E	5.31	E
SN4	1	6.59	E	6.09	E	6.29	E
	2	5.87	E	5.75	E	6.47	E
	3	5.53	E	5.35	E	5.85	E
	4	5.84	E	5.24	E	6.52	E
	5	6.17	E	5.61	E	5.52	E
SN5	1	5.66	E	6.19	E	5.36	E
	2	5.61	E	6.88	E	5.91	E
	3	6.54	E	4.82	E	5.75	E
	4	6.12	E	6.04	E	6.25	E
	5	5.78	E	6.49	E	6.58	E

Appendix G. Electrical Resistance Data after the First 30 Drops, Zero Hour, Leg 1, Board #1 & 2.

	Leg 1						Leg 1					
	Zero hour						Zero hour					
BD#	1						2					
Side	A			B			A			B		
	T0	T30	%	T0	T30	%	T0	T30	%	T0	T30	%
U1	13.2	13.5	2%	14.7	14.8	1%	14.0	14.0	0%	14.1	14.5	3%
U2	13.2	13.2	0%	15.3	15.3	0%	13.4	13.6	1%	13.4	13.4	0%
U3	13.8	13.9	1%	15.4	15.4	0%	14.0	14.5	4%	14.1	14.7	4%
U4	14.2	14.2	0%	14.0	14.5	4%	14.1	14.9	6%	13.2	14.0	6%
U5	13.2	13.5	2%	14.2	14.3	1%	14.3	14.7	3%	14.3	14.3	0%
U6	13.8	14.2	3%	14.0	14.3	2%	13.8	14.0	1%	13.7	13.9	1%
U7	13.6	14.1	4%	13.6	13.6	0%	14.9	15.3	3%	13.4	13.8	3%
U8	13.9	13.9	0%	14.0	14.0	0%	14.3	14.3	0%	14.4	14.6	1%
U9	12.4	12.5	1%	13.7	13.9	1%	14.6	14.7	1%	14.4	14.5	1%
U10	13.6	13.9	2%	14.9	15.2	2%	14.1	14.1	0%	14.4	15.1	5%
U11	14.0	14.5	4%	14.3	14.3	0%	13.9	13.9	0%	14.1	14.2	1%
U12	13.3	14.1	6%	13.2	13.5	2%	14.6	15.1	3%	14.6	14.6	0%
U13	13.0	13.6	5%	13.8	13.9	1%	14.6	14.6	0%	14.9	15.1	1%
U14	13.1	13.1	0%	13.5	13.5	0%	14.6	14.9	2%	14.5	14.5	0%
U15	13.4	13.6	1%	13.4	13.4	0%	14.1	14.2	1%	14.0	14.9	6%

Appendix H. Electrical Resistance Data after the Fist 30 Drops, Zero Hour, Leg 1, Board #3 & 4.

	Leg 1						Leg 1					
	Zero hour						Zero hour					
BD#	3						4					
Side	A			B			A			B		
	T0	T30	%	T0	T30	%	T0	T30	%	T0	T30	%
U1	13.9	14.2	2%	13.4	13.4	0%	13.8	14.5	5%	13.2	13.2	0%
U2	13.6	13.9	2%	13.6	13.6	0%	13.5	13.6	1%	12.9	13.9	8%
U3	12.3	12.9	5%	13.5	13.9	3%	14.1	14.1	0%	14.1	14.3	1%
U4	13.5	13.6	1%	14.0	14.5	4%	13.9	14.9	7%	13.6	13.6	0%
U5	13.9	14.2	2%	12.8	13.1	2%	12.9	12.9	0%	13.4	13.8	3%
U6	13.1	13.1	0%	13.9	13.9	0%	13.5	13.5	0%	12.7	13.2	4%
U7	13.3	13.5	2%	13.7	14.2	4%	13.8	14.2	3%	13.7	13.9	1%
U8	12.3	13.1	7%	13.8	14.2	3%	14.3	14.5	1%	13.5	13.7	1%
U9	14.3	14.4	1%	14.5	14.9	3%	13.7	13.9	1%	12.8	13.2	3%
U10	13.8	13.9	1%	13.6	14.5	7%	12.5	12.5	0%	14.5	14.6	1%
U11	13.8	13.8	0%	14.3	14.3	0%	13.4	13.4	0%	13.6	14.1	4%
U12	14.0	14.1	1%	14.6	14.8	1%	13.0	13.2	2%	13.1	13.5	3%
U13	13.7	14.0	2%	13.9	13.9	0%	13.6	13.7	1%	12.5	13.2	6%
U14	13.0	13.8	6%	13.8	13.9	1%	14.1	14.4	2%	14.0	14.8	6%
U15	14.3	14.3	0%	12.9	12.9	0%	14.5	14.6	1%	13.5	13.6	1%

Appendix I. Electrical Resistance Data after the First 30 Drops, HTS500, Leg 1, Board #1 & 2.

	Leg 1						Leg 1					
	HTS500						HTS500					
BD#	1						2					
Side	A			B			A			B		
	T0	T30	%	T0	T30	%	T0	T30	%	T0	T30	%
U1	14.0	14.2	1%	12.1	12.1	0%	13.5	14.0	4%	12.9	13.1	2%
U2	13.8	14.0	1%	13.9	14.1	1%	13.1	13.3	2%	12.8	13.2	3%
U3	13.7	13.7	0%	13.7	13.7	0%	13.4	13.4	0%	14.4	14.5	1%
U4	14.3	14.6	2%	13.5	13.9	3%	14.0	14.9	6%	13.7	14.7	7%
U5	13.7	13.7	0%	13.9	14.7	6%	13.8	14.0	1%	13.5	13.7	1%
U6	13.5	14.1	4%	13.7	13.7	0%	14.3	14.5	1%	13.9	14.0	1%
U7	13.8	13.8	0%	14.5	14.5	0%	14.6	14.8	1%	14.4	14.6	1%
U8	13.6	13.6	0%	13.6	13.6	0%	14.1	14.1	0%	14.0	14.0	0%
U9	12.8	13.9	9%	13.8	14.0	1%	13.4	13.9	4%	13.2	13.5	2%
U10	14.6	14.6	0%	13.1	13.1	0%	13.4	13.6	1%	14.6	14.7	1%
U11	12.9	13.1	2%	14.2	14.2	0%	14.0	14.2	1%	14.3	14.3	0%
U12	13.2	13.2	0%	14.5	14.6	1%	13.6	13.7	1%	14.6	15.1	3%
U13	13.5	13.8	2%	12.9	13.1	2%	14.1	14.6	4%	14.3	14.5	1%
U14	14.0	14.0	0%	14.3	14.4	1%	14.4	14.1	-2%	13.9	13.9	0%
U15	13.5	13.5	0%	14.5	14.5	0%	14.6	14.8	1%	13.1	13.6	4%

Appendix J. Electrical Resistance Data after the First 30 Drops, HTS500, Leg 1, Board #3 & 4.

	Leg 1						Leg 1					
	HTS500						HTS500					
BD#	3						4					
Side	A			B			A			B		
	T0	T30	%	T0	T30	%	T0	T30	%	T0	T30	%
U1	13.1	13.1	0%	14.0	14.2	1%	12.5	12.6	1%	14.5	14.6	1%
U2	13.5	14.1	4%	13.8	14.5	5%	13.7	13.7	0%	13.6	13.7	1%
U3	14.1	14.6	4%	13.3	14.1	6%	13.9	14.3	3%	13.9	14.2	2%
U4	13.9	14.0	1%	14.2	14.3	1%	14.5	14.9	3%	12.9	12.9	0%
U5	13.5	13.5	0%	12.7	12.8	1%	13.7	13.9	1%	13.4	13.9	4%
U6	12.8	13.2	3%	13.5	13.5	0%	13.6	13.6	0%	13.5	13.5	0%
U7	13.5	13.6	1%	13.9	14.2	2%	13.2	13.5	2%	14.1	14.4	2%
U8	13.5	13.6	1%	13.5	13.5	0%	14.0	14.2	1%	13.6	13.6	0%
U9	13.6	14.1	4%	13.3	13.3	0%	14.5	14.9	3%	13.5	13.9	3%
U10	13.3	14.3	8%	13.3	13.6	2%	13.2	13.3	1%	14.2	14.3	1%
U11	13.9	13.9	0%	14.1	14.8	5%	13.0	13.1	1%	14.1	14.9	6%
U12	13.5	14.1	4%	13.2	13.7	4%	13.9	14.1	1%	12.9	13.6	5%
U13	12.9	12.9	0%	13.7	13.9	1%	14.2	14.2	0%	14.2	14.5	2%
U14	13.4	13.6	1%	13.6	13.6	0%	13.8	13.8	0%	13.2	13.8	5%
U15	14.2	14.5	2%	14.5	14.9	3%	13.6	14.0	3%	13.3	13.4	1%

Appendix K. Electrical Resistance Data after the First 30 Drops, HTS1000, Leg 1, Board #1 & 2.

	Leg 1						Leg 1					
	HTS1000						HTS1000					
BD#	1						2					
Side	A			B			A			B		
	T0	T30	%	T0	T30	%	T0	T30	%	T0	T30	%
U1	13.2	13.2	0%	14.1	14.3	1%	13.6	13.7	1%	14.0	14.0	0%
U2	12.5	12.6	1%	14.8	14.8	0%	14.6	14.6	0%	14.9	22.2	49%
U3	13.9	14.1	1%	13.9	14.5	4%	14.2	14.6	3%	14.6	14.9	2%
U4	14.8	14.8	0%	14.6	14.7	1%	14.8	14.9	1%	14.7	15.0	2%
U5	14.9	15.0	1%	13.2	13.5	2%	13.8	14.1	2%	13.3	13.3	0%
U6	14.3	14.3	0%	14.5	14.5	0%	13.1	13.1	0%	13.7	13.9	1%
U7	15.1	15.3	1%	15.1	15.1	0%	14.1	14.5	3%	13.6	13.6	0%
U8	14.9	14.9	0%	14.5	14.9	3%	14.4	14.8	3%	14.4	14.7	2%
U9	15.2	15.2	0%	13.5	14.0	4%	13.8	13.8	0%	14.2	14.2	0%
U10	15.8	15.9	1%	13.2	13.2	0%	14.3	14.3	0%	14.0	14.0	0%
U11	14.6	14.8	1%	14.1	14.1	0%	13.3	13.3	0%	13.9	20.2	45%
U12	13.8	13.9	1%	14.1	14.3	1%	14.5	14.8	2%	13.5	13.5	0%
U13	13.9	14.3	3%	13.8	14.2	3%	14.1	14.5	3%	14.6	14.7	1%
U14	14.4	15.4	7%	14.4	46.5	223%	14.5	14.5	0%	13.9	13.9	0%
U15	14.2	14.3	1%	14.3	14.4	1%	14.1	14.3	1%	14.2	14.3	1%

Appendix L. Electrical Resistance Data after the First 30 Drops, HTS1000, Leg 1, Board #3 & 4.

	Leg 1						Leg 1					
	HTS1000						HTS1000					
BD#	3						4					
Side	A			B			A			B		
	T0	T30	%	T0	T30	%	T0	T30	%	T0	T30	%
U1	14.2	14.2	0%	13.5	13.7	1%	13.5	13.5	0%	13.5	13.6	1%
U2	14.4	14.5	1%	14.7	14.7	0%	14.6	14.6	0%	14.6	14.6	0%
U3	13.8	14.2	3%	14.2	14.7	4%	13.9	14.4	4%	13.9	14.5	4%
U4	14.6	14.6	0%	14.3	14.3	0%	13.5	13.5	0%	13.8	14.2	3%
U5	13.8	14.1	2%	13.7	14.0	2%	14.7	14.8	1%	14.4	14.4	0%
U6	14.1	14.1	0%	14.4	14.4	0%	14.5	14.6	1%	14.5	14.5	0%
U7	14.6	14.6	0%	14.8	14.9	1%	14.1	14.6	4%	13.1	13.5	3%
U8	13.5	14.4	7%	14.4	14.6	1%	13.9	14.1	1%	14.6	14.8	1%
U9	14.6	14.8	1%	14.2	14.5	2%	13.5	13.6	1%	14.5	14.5	0%
U10	13.5	13.6	1%	14.3	14.3	0%	14.1	14.1	0%	13.2	13.5	2%
U11	14.0	14.0	0%	14.2	14.2	0%	14.0	14.5	4%	13.1	13.2	1%
U12	13.8	13.8	0%	14.5	14.7	1%	14.8	14.8	0%	13.9	14.0	1%
U13	14.4	14.9	3%	14.6	14.9	2%	13.7	14.5	6%	13.2	14.0	6%
U14	14.4	14.4	0%	14.4	14.4	0%	14.7	14.8	1%	14.2	41.2	190%
U15	14.7	14.8	1%	14.1	14.3	1%	14.5	14.5	0%	14.3	14.4	1%

Appendix M. Electrical Resistance Data after the First 30 Drops, Zero Hour, Leg 2, Board #1 & 2.

	Leg 2						Leg 2					
	Zero hour						Zero hour					
BD#	1						2					
SIDE	A			B			A			B		
	T0	T30	%	T0	T30	%	T0	T30	%	T0	T30	%
U1	13.3	13.5	2%	12.7	12.9	2%	14.0	14.0	0%	13.2	13.5	2%
U2	12.3	12.3	0%	12.7	12.7	0%	13.8	14.0	1%	12.7	13.4	6%
U3	12.2	12.2	0%	12.2	12.2	0%	13.4	13.5	1%	12.6	12.7	1%
U4	12.6	12.6	0%	12.8	13.1	2%	13.6	13.9	2%	14.2	14.5	2%
U5	13.2	13.4	2%	13.6	13.8	1%	12.7	13.0	2%	12.5	13.6	9%
U6	12.4	12.1	-2%	13.8	13.8	0%	14.0	14.0	0%	13.1	14.0	7%
U7	13.1	13.1	0%	12.7	12.9	2%	13.9	14.2	2%	12.5	12.8	2%
U8	12.4	12.4	0%	11.6	11.6	0%	13.9	14.0	1%	12.1	13.2	9%
U9	13.3	13.3	0%	12.1	12.5	3%	14.0	13.7	-2%	13.4	13.5	1%
U10	13.1	13.2	1%	11.3	11.4	1%	12.2	12.2	0%	12.0	12.9	8%
U11	12.9	12.9	0%	12.5	12.5	0%	13.9	13.9	0%	13.1	13.7	5%
U12	12.9	13.0	1%	11.9	11.9	0%	13.0	13.1	1%	13.2	13.3	1%
U13	12.9	12.9	0%	12.1	12.7	5%	13.6	13.6	0%	13.6	13.6	0%
U14	12.7	12.7	0%	13.9	14.1	1%	14.6	14.9	2%	13.2	14.5	10%
U15	12.6	12.8	2%	13.0	13.2	2%	14.2	14.2	0%	14.0	14.9	6%

Appendix N. Electrical Resistance Data after the First 30 Drops, Zero Hour, Leg 2, Board # 3 & 4.

	Leg 2						Leg 2					
	Zero hour						Zero hour					
BD#	3						4					
SIDE	A			B			A			B		
	T0	T30	%	T0	T30	%	T0	T30	%	T0	T30	%
U1	13.2	13.2	0%	12.2	13.0	7%	13.7	12.5	-9%	12.7	13.0	2%
U2	13.5	13.9	3%	12.4	13.5	9%	13.6	13.6	0%	13.9	13.9	0%
U3	12.9	12.9	0%	12.1	12.9	7%	13.3	13.1	-2%	13.3	13.3	0%
U4	13.0	13.1	1%	13.1	13.0	-1%	13.5	11.9	-12%	12.5	13.5	8%
U5	12.6	13.1	4%	12.6	12.6	0%	12.8	12.8	0%	13.8	13.8	0%
U6	12.0	12.7	6%	12.0	12.0	0%	12.0	13.4	12%	13.8	14.2	3%
U7	12.5	12.5	0%	12.5	12.1	-3%	12.7	12.6	-1%	12.7	13.4	6%
U8	12.7	12.9	2%	12.7	13.2	4%	13.3	13.7	3%	13.9	14.4	4%
U9	12.8	13.4	5%	12.8	12.9	1%	13.2	11.8	-11%	12.6	13.2	5%
U10	12.3	12.3	0%	12.3	13.5	10%	13.6	12.1	-11%	12.6	13.6	8%
U11	12.4	12.4	0%	12.4	12.0	-3%	12.6	13.6	8%	13.6	13.6	0%
U12	13.3	14.1	6%	13.3	13.1	-2%	13.1	13.2	1%	13.4	13.5	1%
U13	13.1	13.2	1%	13.1	13.8	5%	14.1	12.5	-11%	13.2	13.2	0%
U14	12.8	12.8	0%	12.8	12.6	-2%	12.7	13.4	6%	13.7	13.9	1%
U15	12.2	13.2	8%	12.2	12.0	-2%	13.1	13.6	4%	13.6	13.6	0%

Appendix O. Electrical Resistance Data after the First 30 Drops, HTS500, Leg 2, Board #1 & 2.

	Leg 2						Leg 2					
	HTS500						HTS500					
BD#	1						2					
SIDE	A			B			A			B		
	T0	T30	%	T0	T30	%	T0	T30	%	T0	T30	%
U1	12.9	13.1	2%	13.0	13.2	2%	14.1	14.2	1%	13.5	14.1	4%
U2	12.7	12.8	1%	13.4	13.5	1%	13.2	13.3	1%	12.9	13.2	2%
U3	13.1	13.2	1%	12.5	12.6	1%	14.1	14.2	1%	13.7	14.0	2%
U4	12.3	12.3	0%	12.1	12.4	2%	12.9	12.9	0%	11.8	12.5	6%
U5	12.4	12.6	2%	14.3	14.9	4%	13.5	14.0	4%	12.6	12.9	2%
U6	12.8	12.9	1%	13.8	13.9	1%	12.8	12.9	1%	13.4	13.4	0%
U7	12.8	13.0	2%	12.9	13.1	2%	13.8	14.0	1%	13.2	13.2	0%
U8	11.5	11.7	2%	14.3	14.5	1%	12.5	12.6	1%	13.8	14.0	1%
U9	12.6	12.9	2%	13.5	12.9	-4%	13.6	13.9	2%	12.9	13.5	5%
U10	11.7	11.9	2%	12.4	12.6	2%	13.3	13.5	2%	12.3	12.9	5%
U11	12.5	13.3	6%	13.9	14.7	6%	13.0	13.9	7%	12.1	13.2	9%
U12	13.5	13.7	1%	12.6	12.8	2%	13.5	13.7	1%	13.5	13.5	0%
U13	12.6	12.8	2%	13.1	13.3	2%	12.6	12.6	0%	14.1	14.5	3%
U14	12.2	13.1	7%	13.6	14.5	7%	13.4	14.3	7%	13.6	13.6	0%
U15	12.5	12.7	2%	13.1	12.5	-5%	12.2	12.2	0%	12.5	12.6	1%

Appendix P. Electrical Resistance Data after the First 30 Drops, HTS500, Leg 2, Board #3 & 4.

	Leg 2						Leg 2					
	HTS500						HTS500					
BD#	3						4					
SIDE	A			B			A			B		
	T0	T30	%	T0	T30	%	T0	T30	%	T0	T30	%
U1	13.0	13.0	0%	13.2	13.2	0%	12.5	12.6	1%	12.6	12.6	0%
U2	13.8	14.1	2%	14.1	14.5	3%	12.7	12.7	0%	12.2	12.7	4%
U3	12.3	12.6	2%	14.3	14.3	0%	11.9	12.4	4%	11.9	12.5	5%
U4	13.2	13.5	2%	13.9	13.9	0%	12.5	12.6	1%	11.6	11.6	0%
U5	12.7	12.7	0%	12.8	12.9	1%	11.8	12.3	4%	12.7	12.9	2%
U6	13.5	13.9	3%	12.1	13.2	9%	13.6	13.6	0%	12.1	13.5	12%
U7	12.9	13.6	5%	13.5	14.1	4%	13.0	13.0	0%	13.4	13.4	0%
U8	13.3	13.3	0%	13.2	13.2	0%	12.0	13.2	10%	13.2	13.3	1%
U9	13.5	13.5	0%	13.6	13.8	1%	12.5	12.9	3%	12.7	12.9	2%
U10	14.1	14.3	1%	12.5	12.8	2%	12.2	12.3	1%	12.3	12.3	0%
U11	13.3	13.8	4%	14.1	14.2	1%	12.0	13.1	9%	12.6	12.9	2%
U12	13.2	13.5	2%	13.6	13.7	1%	11.9	12.5	5%	13.1	13.6	4%
U13	13.4	13.8	3%	13.1	13.1	0%	13.2	13.2	0%	12.9	13.2	2%
U14	13.6	13.6	0%	12.4	13.6	10%	13.8	13.8	0%	13.7	13.8	1%
U15	13.5	13.5	0%	13.7	13.9	1%	12.6	12.7	1%	13.0	13.1	1%

Appendix Q. Electrical Resistance Data after the First 30 Drops, HTS1000, Leg 2, Board #1 & 2.

	Leg 2						Leg 2					
	HTS1000						HTS1000					
BD#	1						2					
SIDE	A			B			A			B		
	T0	T30	%	T0	T30	%	T0	T30	%	T0	T30	%
U1	13.3	13.5	2%	13.2	45.1	242%	13.3	13.3	0%	12.7	12.7	0%
U2	12.8	12.9	1%	13.6	13.6	0%	12.8	12.8	0%	12.6	52.8	319%
U3	13.1	13.5	3%	13.1	>1K	#####	13.4	13.4	0%	13.1	13.3	2%
U4	12.6	12.8	2%	13.4	40.8	204%	12.6	12.6	0%	12.5	23.6	89%
U5	13.4	13.4	0%	13.7	13.7	0%	12.6	12.6	0%	12.0	12.5	4%
U6	13.7	13.8	1%	13.6	13.6	0%	13.2	13.2	0%	13.5	13.5	0%
U7	12.7	12.7	0%	13.6	13.6	0%	13.5	13.5	0%	12.6	12.6	0%
U8	13.0	13.7	5%	13.4	13.7	2%	13.4	13.4	0%	12.2	12.4	2%
U9	12.6	12.8	2%	13.9	13.9	0%	13.6	13.6	0%	13.2	13.3	1%
U10	13.1	13.1	0%	13.7	13.7	0%	13.3	13.3	0%	12.7	12.7	0%
U11	13.3	13.5	2%	13.5	13.5	0%	13.5	13.5	0%	12.6	12.6	0%
U12	13.5	13.5	0%	13.2	13.4	2%	13.4	13.4	0%	12.9	13.0	1%
U13	12.9	13.2	2%	13.0	13.0	0%	13.0	13.0	0%	12.5	12.8	2%
U14	13.0	13.0	0%	13.4	13.7	2%	13.1	13.1	0%	12.7	12.7	0%
U15	13.2	13.3	1%	13.0	13.1	1%	12.6	12.6	0%	12.6	12.7	1%

Appendix R. Electrical Resistance Data after the First 30 Drops, HTS1000, Leg 2, Board #3 & 4.

	Leg 2						Leg 2					
	HTS1000						HTS1000					
BD#	3						4					
SIDE	A			B			A			B		
	T0	T30	%	T0	T30	%	T0	T30	%	T0	T30	%
U1	13.0	13.2	2%	12.6	12.6	0%	12.8	12.9	1%	12.9	13.1	2%
U2	13.1	13.2	1%	12.8	24.5	91%	12.8	13.0	2%	13.2	21.1	60%
U3	13.2	13.4	2%	12.4	12.6	2%	12.9	13.0	1%	12.6	12.7	1%
U4	13.5	13.5	0%	13.1	13.2	1%	13.6	13.6	0%	12.9	31.6	145%
U5	12.9	12.9	0%	12.4	12.4	0%	12.8	12.9	1%	13.7	13.8	1%
U6	12.6	12.6	0%	12.5	12.8	2%	13.2	13.2	0%	13.1	13.1	0%
U7	13.4	13.5	1%	12.8	12.8	0%	13.0	13.1	1%	12.6	12.9	2%
U8	12.5	13.0	4%	12.6	12.9	2%	13.2	13.6	3%	13.3	13.7	3%
U9	13.1	13.1	0%	13.1	35.2	169%	13.5	13.5	0%	13.7	13.7	0%
U10	13.3	13.3	0%	12.7	13.0	2%	13.2	13.2	0%	13.3	13.4	1%
U11	13.0	13.1	1%	12.5	12.5	0%	13.0	13.1	1%	12.9	12.9	0%
U12	13.7	13.7	0%	13.0	13.0	0%	12.9	12.9	0%	12.6	12.6	0%
U13	12.9	13.4	4%	12.5	12.6	1%	13.2	13.5	2%	13.2	13.6	3%
U14	12.4	12.6	2%	13.6	13.7	1%	12.8	12.9	1%	12.7	13.0	2%
U15	13.2	13.2	0%	13.0	13.0	0%	13.6	13.6	0%	13.3	41.2	210%

Appendix S. Electrical Resistance Data after the First 30 Drops, Zero Hour, Leg 3, Board #1 & 2.

	Leg 3						Leg 3					
	Zero hour						Zero hour					
BD#	1						2					
SIDE	A			B			A			B		
	T0	T30	%	T0	T30	%	T0	T30	%	T0	T30	%
U1	13.8	14.5	5%	13.2	13.9	5%	13.4	13.6	1%	13.8	14.0	1%
U2	13.7	13.7	0%	12.9	13.7	6%	13.3	13.5	2%	13.7	13.9	1%
U3	14.1	14.1	0%	14.0	14.2	1%	12.9	12.9	0%	13.4	13.7	2%
U4	13.8	13.9	1%	13.0	13.1	1%	13.2	13.8	5%	13.6	14.1	4%
U5	13.5	13.6	1%	12.7	12.8	1%	13.8	13.9	1%	14.2	14.3	1%
U6	13.7	14.1	3%	12.9	13.7	6%	13.5	13.5	0%	13.9	14.0	1%
U7	12.9	12.9	0%	12.1	12.9	7%	13.7	13.7	0%	14.1	14.1	0%
U8	14.3	14.4	1%	13.7	14.1	3%	13.5	14.1	4%	13.9	14.1	1%
U9	13.3	13.3	0%	12.5	13.5	8%	13.4	13.7	2%	13.9	14.5	4%
U10	13.1	13.2	1%	12.3	12.4	1%	13.4	13.6	1%	13.9	14.4	4%
U11	13.7	13.9	1%	12.9	13.9	8%	13.9	14.2	2%	13.3	13.4	1%
U12	13.9	14.0	1%	13.1	13.9	6%	13.6	14.4	6%	14.0	14.0	0%
U13	14.3	14.4	1%	13.5	13.7	1%	13.6	13.9	2%	13.0	13.5	4%
U14	13.2	13.7	4%	13.4	14.0	4%	14.0	14.1	1%	14.4	14.5	1%
U15	13.0	13.8	6%	14.2	14.2	0%	13.1	13.3	2%	13.5	13.6	1%

Appendix T. Electrical Resistance Data after the First 30 Drops, Zero Hour, Leg 3, Board #3 & 4.

	Leg 3						Leg 3					
	Zero hour						Zero hour					
BD#	3						4					
SIDE	A			B			A			B		
	T0	T30	%	T0	T30	%	T0	T30	%	T0	T30	%
U1	13.1	13.3	2%	13.5	13.6	1%	13.4	13.5	1%	13.0	13.3	2%
U2	13.6	13.9	2%	14.0	14.4	3%	13.9	13.9	0%	13.5	13.9	3%
U3	13.1	13.5	3%	13.5	13.9	3%	14.3	14.3	0%	13.9	13.9	0%
U4	13.2	13.3	1%	13.6	13.6	0%	13.7	13.7	0%	13.3	13.5	2%
U5	13.8	13.9	1%	14.2	14.6	3%	13.6	13.9	2%	14.2	14.2	0%
U6	13.4	14.1	5%	13.8	13.9	1%	14.2	14.2	0%	13.8	14.0	1%
U7	13.9	14.0	1%	14.3	14.3	0%	13.8	13.8	0%	13.4	13.5	1%
U8	13.5	13.8	2%	13.9	14.1	1%	14.0	14.5	4%	13.6	13.9	2%
U9	13.8	13.9	1%	14.2	14.2	0%	14.0	14.1	1%	13.6	13.6	0%
U10	13.4	13.4	0%	13.8	13.9	1%	13.8	14.0	1%	13.4	13.6	1%
U11	13.7	13.7	0%	14.1	14.1	0%	13.4	13.8	3%	13.0	13.8	6%
U12	13.5	13.8	2%	13.9	14.0	1%	13.8	13.8	0%	13.4	13.5	1%
U13	13.5	13.9	3%	13.9	14.4	4%	14.1	14.1	0%	13.7	13.7	0%
U14	14.1	14.1	0%	13.5	13.7	1%	14.2	14.5	2%	12.8	13.1	2%
U15	12.9	13.2	2%	13.3	13.3	0%	13.5	13.5	0%	14.1	14.1	0%

Appendix U. Electrical Resistance Data after the First 30 Drops, HTS500, Leg 3, Board #1 & 2.

	Leg 3						Leg 3					
	HTS500						HTS500					
BD#	1						2					
SIDE	A			B			A			B		
	T0	T30	%	T0	T30	%	T0	T30	%	T0	T30	%
U1	13.5	13.7	1%	13.1	13.2	1%	14.2	14.2	0%	13.9	13.9	0%
U2	13.3	13.6	2%	13.6	14.0	3%	13.7	13.9	1%	13.1	13.5	3%
U3	13.8	13.8	0%	13.5	13.9	3%	13.3	13.3	0%	13.5	13.6	1%
U4	13.3	13.4	1%	13.3	13.9	5%	13.4	13.9	4%	12.1	12.1	0%
U5	12.9	13.5	5%	13.4	13.4	0%	13.6	14.1	4%	12.8	13.4	5%
U6	13.3	13.8	4%	12.8	13.0	2%	14.0	14.1	1%	13.4	13.4	0%
U7	13.0	13.3	2%	13.2	13.2	0%	13.2	13.9	5%	13.0	13.5	4%
U8	12.8	13.2	3%	13.6	13.8	1%	13.3	13.6	2%	13.3	14.0	5%
U9	13.1	13.2	1%	13.8	13.8	0%	14.1	14.5	3%	13.1	13.6	4%
U10	13.5	13.9	3%	14.0	14.0	0%	13.7	13.7	0%	12.1	13.2	9%
U11	12.8	13.6	6%	13.2	13.2	0%	13.8	13.9	1%	13.2	13.9	5%
U12	13.6	13.9	2%	13.0	13.2	2%	13.4	13.4	0%	13.1	13.4	2%
U13	13.1	13.1	0%	13.4	13.4	0%	14.2	14.8	4%	13.9	14.1	1%
U14	13.6	14.1	4%	13.1	13.1	0%	13.6	14.2	4%	13.6	13.6	0%
U15	13.9	13.9	0%	13.0	13.3	2%	13.7	14.1	3%	12.2	13.1	7%

Appendix V. Electrical Resistance Data after the First 30 Drops, HTS500, Leg 3, Board #3 & 4.

	Leg 3						Leg 3					
	HTS500						HTS500					
BD#	3						4					
SIDE	A			B			A			B		
	T0	T30	%	T0	T30	%	T0	T30	%	T0	T30	%
U1	14.1	14.5	3%	14.3	14.3	0%	13.6	13.6	0%	13.6	13.8	1%
U2	13.3	13.3	0%	13.1	13.5	3%	13.7	14.4	5%	13.6	13.7	1%
U3	13.6	13.6	0%	14.0	14.0	0%	13.8	14.3	4%	13.9	13.9	0%
U4	13.7	13.7	0%	13.9	14.2	2%	14.0	14.3	2%	12.9	13.5	5%
U5	13.9	14.3	3%	14.1	14.1	0%	13.7	13.8	1%	13.2	13.6	3%
U6	14.3	14.5	1%	14.0	14.0	0%	13.4	13.4	0%	13.8	13.9	1%
U7	13.5	13.9	3%	14.3	14.7	3%	13.5	13.6	1%	13.4	13.4	0%
U8	13.6	13.6	0%	14.0	14.1	1%	14.2	14.2	0%	13.3	13.3	0%
U9	14.4	14.5	1%	13.4	13.8	3%	14.1	14.2	1%	12.8	13.3	4%
U10	14.0	14.1	1%	14.3	14.5	1%	14.0	14.4	3%	13.3	14.0	5%
U11	14.1	14.2	1%	13.8	13.9	1%	13.3	13.6	2%	13.7	13.7	0%
U12	13.7	13.9	1%	13.0	13.3	2%	12.7	13.6	7%	13.8	14.0	1%
U13	14.5	14.5	0%	13.5	13.6	1%	13.7	13.8	1%	12.9	13.2	2%
U14	13.9	13.9	0%	12.9	13.1	2%	13.5	13.5	0%	13.8	14.2	3%
U15	14.0	14.0	0%	12.6	13.1	4%	13.6	13.7	1%	13.5	14.0	4%

Appendix W. Electrical Resistance Data after the First 30 Drops, HTS1000, Leg 3, Board #1 & 2.

	Leg 3						Leg 3					
	HTS1000						HTS1000					
BD#	1						2					
SIDE	A			B			A			B		
	T0	T30	%	T0	T30	%	T0	T30	%	T0	T30	%
U1	13.5	13.5	0%	13.5	13.5	0%	13.2	13.3	1%	13.8	13.9	1%
U2	12.9	13.1	2%	13.3	13.3	0%	12.7	13.0	2%	13.0	13.2	2%
U3	13.2	13.3	1%	12.8	12.9	1%	13.6	13.9	2%	13.5	13.8	2%
U4	13.5	13.5	0%	13.0	13.1	1%	13.4	13.4	0%	12.1	12.1	0%
U5	13.3	13.5	2%	12.9	41.5	222%	13.3	13.3	0%	12.8	12.8	0%
U6	13.8	13.8	0%	12.1	12.1	0%	13.0	13.4	3%	13.6	13.6	0%
U7	12.8	13.4	5%	12.9	12.9	0%	13.2	13.2	0%	13.3	13.3	0%
U8	13.3	13.8	4%	13.0	13.5	4%	13.3	13.4	1%	13.9	14.1	1%
U9	13.7	13.8	1%	13.7	13.7	0%	13.1	13.3	2%	13.1	13.3	2%
U10	13.5	13.5	0%	12.8	12.8	0%	13.4	13.4	0%	12.2	12.5	2%
U11	13.8	13.9	1%	13.6	13.7	1%	13.8	13.9	1%	13.2	46.3	251%
U12	13.0	13.4	3%	12.8	12.8	0%	13.7	13.7	0%	13.1	13.1	0%
U13	13.2	13.2	0%	13.2	13.5	2%	13.2	13.5	2%	13.5	13.8	2%
U14	13.0	13.1	1%	13.8	13.8	0%	13.7	13.8	1%	12.1	12.5	3%
U15	13.1	13.1	0%	13.0	13.1	1%	13.6	13.6	0%	12.8	12.8	0%

Appendix X. Electrical Resistance Data after the First 30 Drops, HTS1000, Leg 3, Board #3 & 4.

	Leg 3						Leg 3					
	HTS1000						HTS1000					
BD#	3						4					
SIDE	A			B			A			B		
	T0	T30	%	T0	T30	%	T0	T30	%	T0	T30	%
U1	13.1	13.3	2%	13.3	13.3	0%	13.6	13.6	0%	13.2	13.3	1%
U2	12.5	12.6	1%	13.1	13.5	3%	13.5	13.7	1%	13.4	13.4	0%
U3	13.4	13.6	1%	13.0	13.2	2%	13.8	14.3	4%	13.7	14.0	2%
U4	13.2	13.5	2%	13.9	14.2	2%	13.0	13.1	1%	12.8	13.1	2%
U5	13.7	13.7	0%	13.1	13.5	3%	13.7	13.8	1%	13.4	13.4	0%
U6	12.6	12.6	0%	14.0	14.0	0%	13.4	13.4	0%	13.0	13.3	2%
U7	12.8	13.0	2%	13.3	13.7	3%	13.5	13.6	1%	13.1	13.2	1%
U8	13.4	13.5	1%	13.0	13.6	5%	13.2	13.9	5%	13.2	13.8	5%
U9	13.3	13.3	0%	13.4	13.8	3%	13.1	13.3	2%	13.1	13.1	0%
U10	13.0	13.1	1%	14.3	14.5	1%	14.1	14.2	1%	13.5	13.7	1%
U11	13.6	13.6	0%	13.8	13.9	1%	13.3	13.6	2%	13.3	13.3	0%
U12	13.1	13.1	0%	13.0	13.3	2%	13.7	13.6	-1%	13.4	13.5	1%
U13	13.5	13.7	1%	13.5	13.8	2%	12.7	13.1	3%	13.6	13.9	2%
U14	12.5	12.6	1%	12.9	13.1	2%	13.1	13.5	3%	12.7	12.7	0%
U15	12.8	12.8	0%	12.6	13.1	4%	13.6	13.7	1%	13.1	47.7	264%

Appendix Y. Electrical Resistance Data after the First 30 Drops, Zero Hour, Leg 4, Board #1 & 2.

	Leg 4						Leg 4					
	Zero hour						Zero hour					
BD#	1						2					
SIDE	A			B			A			B		
	T0	T30	%	T0	T30	%	T0	T30	%	T0	T30	%
U1	13	13.3	2%	13.5	13.8	2%	13.6	13.8	1%	13.9	14.0	1%
U2	13.1	13.2	1%	12.9	13.4	4%	13.4	13.4	0%	13.8	14.1	2%
U3	13.5	13.6	1%	13.5	13.7	1%	13.3	13.5	2%	14.0	14.5	4%
U4	12.8	13.1	2%	13.1	13.1	0%	12.2	12.5	2%	12.6	12.9	2%
U5	12.9	13.5	5%	13.7	13.8	1%	12.7	13.0	2%	13.0	13.0	0%
U6	13.4	13.4	0%	12.9	13.5	5%	13.3	13.3	0%	13.9	14.0	1%
U7	13.6	13.6	0%	13.7	13.8	1%	12.8	13.1	2%	13.4	13.6	1%
U8	12.9	13.7	6%	13.5	13.9	3%	13.1	13.9	6%	13.7	13.9	1%
U9	13.5	13.8	2%	14.0	14.0	0%	13.2	13.7	4%	13.3	13.6	2%
U10	14	14.3	2%	14.1	14.5	3%	13.1	13.7	5%	13.5	13.5	0%
U11	13.5	13.5	0%	13.7	13.7	0%	13.0	14.0	8%	13.7	13.9	1%
U12	13.8	13.9	1%	13.5	14.1	4%	13.2	13.4	2%	13.6	13.7	1%
U13	13.3	13.3	0%	13.4	13.4	0%	12.9	12.9	0%	13.6	13.6	0%
U14	13	13.1	1%	12.9	13.1	2%	13.3	13.5	2%	13.9	14.2	2%
U15	13.5	13.7	1%	13.3	13.9	5%	13.2	13.6	3%	13.8	14.0	1%

Appendix Z. Electrical Resistance Data after the First 30 Drops, Zero Hour, Leg 4, Board #3 & 4.

	Leg 4						Leg 4					
	Zero hour						Zero hour					
BD#	3						4					
SIDE	A			B			A			B		
	T0	T30	%	T0	T30	%	T0	T30	%	T0	T30	%
U1	13.1	13.1	0%	13.4	13.6	1%	13.6	13.9	2%	13.9	14.0	1%
U2	12.8	13.0	2%	13.0	13.2	2%	13.5	13.9	3%	13.7	13.9	1%
U3	12.9	13.4	4%	13.3	13.5	2%	13.7	14.0	2%	13.6	13.0	-4%
U4	12.6	12.9	2%	12.5	12.9	3%	12.3	12.8	4%	12.5	13.7	10%
U5	13.1	13.3	2%	13.5	13.6	1%	12.7	12.7	0%	13.0	13.2	2%
U6	13.1	13.2	1%	13.0	13.3	2%	13.6	13.8	1%	13.6	13.9	2%
U7	12.7	13.4	6%	13.5	13.6	1%	13.1	13.1	0%	13.1	13.1	0%
U8	13.3	13.5	2%	13.6	13.7	1%	13.4	13.5	1%	13.4	13.5	1%
U9	13.0	13.6	5%	13.1	13.8	5%	13.0	13.7	5%	13.5	13.5	0%
U10	13.6	14.1	4%	13.7	14.3	4%	13.2	13.4	2%	13.4	13.4	0%
U11	13.2	13.3	1%	12.8	13.5	5%	13.4	13.4	0%	13.3	13.3	0%
U12	13.7	13.7	0%	13.1	13.9	6%	13.3	13.8	4%	13.5	13.9	3%
U13	13.1	13.1	0%	13.2	13.2	0%	13.3	13.6	2%	13.2	13.2	0%
U14	12.7	12.9	2%	12.5	12.9	3%	13.6	13.6	0%	13.6	13.6	0%
U15	13.5	13.5	0%	13.3	13.7	3%	13.5	13.9	3%	13.5	14.0	4%

Appendix AA. Electrical Resistance Data after the First 30 Drops, HTS500, Leg 4, Board #1 & 2.

	Leg 4						Leg 4					
	HTS500						HTS500					
BD#	1						2					
SIDE	A			B			A			B		
	T0	T30	%	T0	T30	%	T0	T30	%	T0	T30	%
U1	13.6	13.8	1%	13.6	13.8	1%	13.1	13.2	1%	13.2	13.3	1%
U2	13.0	13.3	2%	13.3	14.0	5%	14.0	14.1	1%	13.6	13.6	0%
U3	13.1	13.5	3%	12.5	12.6	1%	13.0	13.3	2%	13.7	13.7	0%
U4	12.6	12.9	2%	13.1	13.4	2%	14.2	14.5	2%	13.2	13.2	0%
U5	13.0	13.8	6%	13.7	14.4	5%	13.0	13.1	1%	13.2	13.9	5%
U6	13.4	13.3	-1%	13.5	13.6	1%	13.2	13.2	0%	13.5	13.5	0%
U7	13.8	13.8	0%	13.3	13.6	2%	13.8	13.9	1%	13.0	13.0	0%
U8	13.3	13.5	2%	13.7	13.8	1%	13.9	14.0	1%	13.5	13.5	0%
U9	12.2	12.9	6%	13.3	13.3	0%	13.2	13.2	0%	13.6	13.8	1%
U10	13.5	14.2	5%	13.1	13.7	5%	13.9	14.3	3%	13.4	13.4	0%
U11	13.5	13.5	0%	13.2	13.4	2%	13.8	13.9	1%	13.2	13.3	1%
U12	12.6	12.7	1%	13.7	14.0	2%	13.7	13.7	0%	13.3	13.4	1%
U13	12.9	12.9	0%	13.1	13.3	2%	13.5	13.8	2%	13.1	14.0	7%
U14	13.3	13.4	1%	13.4	13.4	0%	13.6	13.6	0%	13.4	13.7	2%
U15	13.6	13.6	0%	13.7	13.8	1%	13.4	13.8	3%	13.1	13.2	1%

Appendix AB. Electrical Resistance Data after the First 30 Drops, HTS500, Leg 4, Board #3 & 4.

	Leg 4						Leg 4					
	HTS500						HTS500					
BD#	3						4					
SIDE	A			B			A			B		
	T0	T30	%	T0	T30	%	T0	T30	%	T0	T30	%
U1	12.8	13.0	2%	13.5	13.5	0%	13.3	13.6	2%	14.0	14.2	1%
U2	13.7	13.8	1%	13.9	14.0	1%	13.7	13.8	1%	13.5	13.7	1%
U3	12.7	13.4	6%	14.0	14.5	4%	12.4	12.4	0%	13.9	13.9	0%
U4	13.9	14.0	1%	13.5	13.9	3%	13.0	13.2	2%	13.0	13.3	2%
U5	12.7	13.1	3%	13.5	13.8	2%	13.9	14.2	2%	13.5	14.2	5%
U6	12.9	13.3	3%	13.8	13.9	1%	13.3	13.4	1%	13.3	13.7	3%
U7	13.5	13.6	1%	13.3	14.0	5%	12.9	13.4	4%	13.8	14.2	3%
U8	13.6	13.6	0%	13.8	14.5	5%	13.1	13.6	4%	13.6	13.9	2%
U9	12.9	13.1	2%	13.9	13.9	0%	12.7	13.1	3%	13.3	13.3	0%
U10	13.6	14.2	4%	13.7	14.5	6%	13.5	13.5	0%	14.1	14.6	4%
U11	13.5	13.9	3%	13.5	13.7	1%	12.9	13.2	2%	13.5	13.9	3%
U12	13.4	13.7	2%	13.6	13.6	0%	13.5	13.8	2%	13.0	13.1	1%
U13	13.2	13.2	0%	13.4	13.5	1%	13.1	13.1	0%	13.3	13.3	0%
U14	13.3	13.9	5%	13.7	13.7	0%	12.6	13.2	5%	13.4	13.8	3%
U15	13.1	13.6	4%	13.4	13.8	3%	13.3	13.6	2%	13.7	14.0	2%

Appendix AC. Electrical Resistance Data after the First 30 Drops, HTS1000, Leg 4, Board #1 & 2.

	Leg 4						Leg 4					
	HTS1000						HTS1000					
BD#	1						2					
SIDE	A			B			A			B		
	T0	T30	%	T0	T30	%	T0	T30	%	T0	T30	%
U1	13.5	13.5	0%	13.2	13.2	0%	13.1	13.2	1%	13.2	13.3	1%
U2	12.9	13.1	2%	13.6	13.6	0%	12.5	12.6	1%	12.8	12.8	0%
U3	13.2	13.3	1%	13.1	13.4	2%	12.5	13.3	6%	13.0	13.5	4%
U4	13.5	13.5	0%	13.4	13.4	0%	13.2	13.2	0%	13.7	13.8	1%
U5	13.3	13.5	2%	13.7	13.7	0%	12.6	12.6	0%	13.0	13.0	0%
U6	13.8	13.8	0%	13.6	13.6	0%	13.1	13.2	1%	13.3	13.3	0%
U7	12.8	13.4	5%	13.6	13.6	0%	12.6	13.3	6%	13.8	13.8	0%
U8	13.3	13.8	4%	13.4	13.7	2%	13.3	13.5	2%	13.9	14.1	1%
U9	13.7	13.8	1%	13.9	13.9	0%	12.7	12.7	0%	13.2	13.5	2%
U10	13.5	13.5	0%	13.7	13.7	0%	13.6	13.6	0%	13.8	13.8	0%
U11	13.8	13.9	1%	13.5	13.5	0%	13.0	13.1	1%	13.7	13.7	0%
U12	13.0	13.4	3%	13.2	13.4	2%	13.0	13.0	0%	13.6	13.8	1%
U13	13.2	13.2	0%	13.0	13.0	0%	12.6	13.4	6%	13.7	14.0	2%
U14	13.0	13.1	1%	13.4	13.7	2%	13.1	13.6	4%	13.3	13.3	0%
U15	13.1	13.1	0%	13.0	13.1	1%	13.4	13.4	0%	13.9	13.9	0%

Appendix AD. Electrical Resistance Data after the First 30 Drops, HTS1000, Leg 4, Board #3 & 4.

	Leg 4						Leg 4					
	HTS1000						HTS1000					
BD#	3						4					
SIDE	A			B			A			B		
	T0	T30	%	T0	T30	%	T0	T30	%	T0	T30	%
U1	13.4	13.4	0%	13.8	13.8	0%	13.0	13.0	0%	13.5	13.7	1%
U2	13.8	13.9	1%	13.2	13.2	0%	12.5	12.9	3%	13.0	13.0	0%
U3	12.8	13.5	5%	13.5	13.9	3%	13.1	13.6	4%	13.1	13.5	3%
U4	13.3	13.5	2%	13.5	13.7	1%	13.7	13.8	1%	13.5	13.8	2%
U5	13.0	13.0	0%	13.0	13.0	0%	13.3	13.3	0%	13.3	13.3	0%
U6	13.1	13.1	0%	13.6	13.8	1%	13.2	13.2	0%	13.6	13.6	0%
U7	13.5	13.6	1%	12.8	12.9	1%	12.8	13.1	2%	12.8	13.4	5%
U8	13.6	13.9	2%	13.0	13.7	5%	13.2	13.9	5%	13.0	13.8	6%
U9	12.7	13.0	2%	12.8	13.5	5%	13.6	13.6	0%	13.3	13.3	0%
U10	13.6	13.6	0%	13.3	13.3	0%	13.7	13.8	1%	13.8	13.9	1%
U11	13.3	13.3	0%	13.2	13.2	0%	13.0	13.3	2%	13.4	13.4	0%
U12	13.0	13.3	2%	12.6	12.6	0%	13.6	13.6	0%	13.1	13.1	0%
U13	13.1	13.4	2%	13.5	13.9	3%	12.9	13.3	3%	13.0	13.3	2%
U14	13.6	13.7	1%	13.7	13.8	1%	13.0	13.1	1%	13.2	13.6	3%
U15	13.5	13.5	0%	13.0	13.1	1%	13.5	13.5	0%	13.6	13.6	0%

Appendix AE. Electrical Resistance Data after the First 30 Drops, Zero Hour, Leg 5, Board #1 & 2.

	Leg 5						Leg 5					
	Zero hour						Zero hour					
BD#	1						2					
SIDE	A			B			A			B		
	T0	T30	%	T0	T30	%	T0	T30	%	T0	T30	%
U1	13.2	13.4	2%	12.6	12.8	2%	13.9	13.9	0%	13.1	13.4	2%
U2	12.2	12.2	0%	12.6	12.6	0%	13.7	13.9	1%	12.6	13.3	6%
U3	12.1	12.5	3%	12.3	12.5	2%	13.5	13.6	1%	12.7	12.8	1%
U4	12.5	12.6	1%	12.9	13.2	2%	13.7	14.0	2%	13.3	13.6	2%
U5	13.1	13.3	2%	13.7	13.9	1%	12.8	13.1	2%	12.6	13.7	9%
U6	12.2	12.7	4%	13.6	13.6	0%	13.8	14.1	2%	12.9	13.8	7%
U7	13.9	14.0	1%	12.5	13.0	4%	13.7	13.9	1%	13.3	13.6	2%
U8	13.2	13.3	1%	13.4	13.4	0%	13.7	13.8	1%	13.9	14.1	1%
U9	13.1	13.1	0%	13.9	14.0	1%	13.8	13.9	1%	13.2	13.3	1%
U10	12.9	13.0	1%	13.1	13.3	2%	12.0	12.5	4%	12.8	13.0	2%
U11	13.6	13.9	2%	12.2	12.5	2%	13.6	13.6	0%	12.8	13.4	5%
U12	12.6	12.7	1%	12.6	13.0	3%	12.7	13.0	2%	12.9	13.0	1%
U13	13.2	13.2	0%	12.4	13.0	5%	13.9	13.9	0%	13.9	13.9	0%
U14	13.0	13.2	2%	13.2	13.4	2%	12.9	13.2	2%	13.5	14.8	10%
U15	12.9	13.1	2%	13.3	13.5	2%	13.5	13.6	1%	13.3	13.3	0%

Appendix AF. Electrical Resistance Data after the First 30 Drops, Zero Hour, Leg 5, Board #3 & 4.

	Leg 5						Leg 5					
	Zero hour						Zero hour					
BD#	3						4					
SIDE	A			B			A			B		
	T0	T30	%	T0	T30	%	T0	T30	%	T0	T30	%
U1	13.1	13.1	0%	12.1	12.9	7%	13.6	13.7	1%	12.6	12.9	2%
U2	13.4	13.8	3%	13.3	13.4	1%	13.5	13.5	0%	13.8	13.8	0%
U3	13.0	13.0	0%	12.8	13.0	2%	13.2	13.3	1%	13.2	13.2	0%
U4	13.1	13.2	1%	13.2	13.1	-1%	13.4	13.6	1%	12.4	12.6	2%
U5	12.7	13.2	4%	12.7	12.7	0%	12.7	12.7	0%	13.7	13.7	0%
U6	12.8	13.0	2%	13.0	11.8	-9%	12.8	13.2	3%	13.6	13.8	1%
U7	13.3	13.4	1%	13.8	14.0	1%	12.5	12.8	2%	12.5	13.2	6%
U8	13.5	13.7	1%	12.5	13.0	4%	13.1	13.5	3%	13.7	14.0	2%
U9	12.6	13.2	5%	12.6	12.7	1%	13.0	13.5	4%	12.4	13.0	5%
U10	13.1	13.1	0%	13.1	13.3	2%	13.4	13.7	2%	13.4	13.4	0%
U11	13.5	13.8	2%	13.3	13.5	2%	12.7	13.0	2%	13.7	13.7	0%
U12	13.0	13.3	2%	13.2	13.5	2%	13.2	13.3	1%	13.5	13.6	1%
U13	13.6	13.7	1%	13.6	13.9	2%	12.6	13.0	3%	13.7	13.7	0%
U14	13.3	13.3	0%	13.3	13.3	0%	13.2	13.8	5%	13.2	13.5	2%
U15	12.7	13.0	2%	12.7	12.9	2%	13.6	13.9	2%	13.1	13.1	0%

Appendix AG. Electrical Resistance Data after the First 30 Drops, HTS500, Leg 5, Board #1 & 2.

	Leg 5						Leg 5					
	HTS500						HTS500					
BD#	1						2					
SIDE	A			B			A			B		
	T0	T30	%	T0	T30	%	T0	T30	%	T0	T30	%
U1	13.3	13.5	2%	13.4	13.6	1%	12.5	12.6	1%	13.9	14.0	1%
U2	13.1	13.2	1%	13.8	13.9	1%	13.6	13.7	1%	13.3	13.6	2%
U3	13.5	13.6	1%	12.9	13.0	1%	13.5	13.8	2%	14.0	14.2	1%
U4	12.7	12.9	2%	12.5	12.8	2%	13.3	13.3	0%	12.6	12.9	2%
U5	12.8	13.0	2%	12.7	13.3	5%	13.9	14.1	1%	13.0	13.3	2%
U6	13.2	13.3	1%	13.2	13.3	1%	13.2	13.3	1%	13.5	13.8	2%
U7	13.2	13.4	2%	13.3	13.5	2%	12.6	12.8	2%	13.6	13.6	0%
U8	12.0	12.5	4%	13.0	13.1	1%	13.0	13.1	1%	13.0	13.4	3%
U9	13.1	13.4	2%	13.2	13.4	2%	14.1	14.2	1%	13.4	13.6	1%
U10	12.2	12.4	2%	12.9	13.1	2%	13.8	14.0	1%	13.6	13.8	1%
U11	13.0	13.8	6%	13.4	13.5	1%	13.5	13.9	3%	12.6	13.1	4%
U12	14.0	14.2	1%	13.1	13.3	2%	13.0	13.4	3%	13.0	13.4	3%
U13	12.5	12.7	2%	13.0	13.2	2%	12.5	12.8	2%	13.7	14.0	2%
U14	13.1	13.2	1%	13.5	13.6	1%	13.3	13.6	2%	13.5	13.5	0%
U15	12.4	12.6	2%	13.0	13.4	3%	12.1	12.3	2%	12.4	12.5	1%

Appendix AH. Electrical Resistance Data after the First 30 Drops, HTS500, Leg 5, Board #3 & 4.

	Leg 5						Leg 5					
	HTS500						HTS500					
BD#	3						4					
SIDE	A			B			A			B		
	T0	T30	%	T0	T30	%	T0	T30	%	T0	T30	%
U1	13.4	13.6	1%	13.2	13.2	0%	13.4	13.4	0%	12.7	12.8	1%
U2	14.0	14.1	1%	14.0	14.2	1%	13.3	13.7	3%	12.9	12.9	0%
U3	12.7	13.0	2%	12.5	12.8	2%	13.5	13.8	2%	13.1	13.6	4%
U4	12.6	12.7	1%	13.4	13.7	2%	14.1	14.1	0%	12.7	13.0	2%
U5	13.1	13.1	0%	12.9	12.9	0%	13.0	13.1	1%	13.0	13.1	1%
U6	13.4	13.6	1%	13.7	14.0	2%	12.3	12.6	2%	13.8	13.8	0%
U7	13.3	13.4	1%	13.1	13.6	4%	13.7	13.9	1%	13.2	13.5	2%
U8	13.0	13.4	3%	13.4	13.4	0%	13.4	13.6	1%	14.0	14.0	0%
U9	12.9	13.1	2%	13.8	14.0	1%	12.8	13.4	5%	13.6	13.8	1%
U10	13.4	13.6	1%	13.5	13.9	3%	12.6	13.0	3%	13.8	14.0	1%
U11	13.2	13.7	4%	14.0	14.1	1%	13.4	13.5	1%	13.6	13.7	1%
U12	13.1	13.4	2%	13.5	13.6	1%	13.8	13.9	1%	13.5	13.8	2%
U13	13.3	13.7	3%	13.0	13.0	0%	13.4	13.8	3%	13.7	13.9	1%
U14	13.5	13.5	0%	12.3	12.6	2%	13.9	13.9	0%	13.9	14.1	1%
U15	13.4	13.4	0%	13.6	13.8	1%	12.8	12.9	1%	13.8	13.8	0%

Appendix AI. Electrical Resistance Data after the First 30 Drops, HTS1000, Leg 5, Board #1 & 2.

	Leg 5						Leg 5					
	HTS1000						HTS1000					
BD#	1						2					
SIDE	A			B			A			B		
	T0	T30	%	T0	T30	%	T0	T30	%	T0	T30	%
U1	12.0	12.5	4%	13.5	13.6	1%	12.6	12.7	1%	13.2	13.6	3%
U2	12.6	12.8	2%	13.1	13.5	3%	13.5	13.8	2%	13.3	13.3	0%
U3	12.8	13.0	2%	13.6	13.9	2%	13.5	13.5	0%	13.0	13.1	1%
U4	12.9	12.9	0%	12.9	12.8	-1%	13.1	13.3	2%	13.1	13.5	3%
U5	13.5	13.6	1%	12.6	12.7	1%	13.8	14.0	1%	12.8	13.0	2%
U6	12.9	13.0	1%	13.9	13.9	0%	12.3	12.4	1%	13.5	13.8	2%
U7	13.2	13.7	4%	12.3	12.6	2%	13.5	13.7	1%	13.0	13.3	2%
U8	13.3	13.7	3%	13.7	13.9	1%	13.5	13.9	3%	12.9	13.3	3%
U9	12.8	12.8	0%	13.5	13.6	1%	13.9	14.4	4%	12.6	12.7	1%
U10	12.9	13.1	2%	13.4	13.7	2%	13.1	13.6	4%	13.5	13.7	1%
U11	13.2	13.3	1%	12.9	13.2	2%	13.3	13.5	2%	13.1	13.3	2%
U12	13.8	13.9	1%	12.6	12.9	2%	13.1	13.1	0%	13.3	13.3	0%
U13	12.8	13.1	2%	13.1	13.1	0%	13.2	13.6	3%	13.8	14.3	4%
U14	13.4	13.5	1%	12.4	12.7	2%	13.8	14.5	5%	12.9	13.4	4%
U15	13.1	13.3	2%	13.3	13.4	1%	13.9	14.4	4%	13.1	13.1	0%

Appendix AJ. Electrical Resistance Data after the First 30 Drops, HTS1000, Leg 5, Board #3 & 4.

	Leg 5						Leg 5					
	HTS1000						HTS1000					
BD#	3						4					
SIDE	A			B			A			B		
	T0	T30	%	T0	T30	%	T0	T30	%	T0	T30	%
U1	13.5	13.5	0%	13.0	13.1	1%	13.3	13.4	1%	13.4	13.5	1%
U2	12.8	13.0	2%	13.5	13.6	1%	13.3	13.5	2%	12.9	13.0	1%
U3	12.8	13.2	3%	13.2	13.2	0%	13.4	13.5	1%	13.1	13.2	1%
U4	13.6	13.7	1%	13.4	13.4	0%	13.1	13.2	1%	13.4	14.1	5%
U5	13.2	13.5	2%	13.3	13.3	0%	13.3	13.4	1%	13.2	14.3	8%
U6	13.2	13.2	0%	13.7	13.9	1%	12.7	13.7	8%	13.6	13.6	0%
U7	13.2	13.3	1%	13.5	13.7	1%	13.5	13.6	1%	13.1	13.4	2%
U8	13.6	13.9	2%	12.8	13.5	5%	13.7	14.1	3%	12.8	13.1	2%
U9	13.4	13.4	0%	12.6	13.0	3%	13.0	13.3	2%	13.0	13.2	2%
U10	13.0	13.1	1%	12.9	13.1	2%	13.7	13.7	0%	12.8	12.9	1%
U11	13.5	13.8	2%	13.2	13.5	2%	12.5	12.9	3%	13.4	13.4	0%
U12	13.2	13.7	4%	13.8	14.0	1%	13.4	13.4	0%	13.1	13.1	0%
U13	12.7	13.2	4%	13.5	13.7	1%	13.7	14.0	2%	13.7	14.0	2%
U14	13.0	13.0	0%	13.6	13.6	0%	13.3	13.4	1%	13.2	13.5	2%
U15	13.7	13.8	1%	13.2	13.5	2%	13.1	13.8	5%	12.8	13.1	2%

Appendix AK. Electrical Resistance Data after the First 30 Drops, Zero Hour, Leg 6, Board #1 & 2.

	Leg 6						Leg 6					
	Zero hour						Zero hour					
BD#	1						2					
SIDE	A			B			A			B		
	T0	T30	%	T0	T30	%	T0	T30	%	T0	T30	%
U1	13.1	13.4	2%	13.6	13.9	2%	13.7	13.9	1%	12.0	12.5	4%
U2	13.2	13.3	1%	13.0	13.5	4%	13.5	13.5	0%	13.9	14.0	1%
U3	13.6	13.7	1%	13.6	13.8	1%	13.4	13.6	1%	13.1	13.6	4%
U4	13.0	13.3	2%	13.3	13.3	0%	12.4	12.7	2%	12.4	12.7	2%
U5	13.1	13.5	3%	13.9	14.0	1%	12.9	13.2	2%	12.8	12.8	0%
U6	13.6	13.6	0%	13.1	13.7	5%	13.5	13.5	0%	13.7	13.8	1%
U7	13.8	14.0	1%	13.9	14.0	1%	13.0	13.3	2%	13.2	13.4	2%
U8	13.1	13.2	1%	13.7	14.1	3%	13.4	14.0	4%	14.0	14.2	1%
U9	13.6	13.9	2%	13.1	13.1	0%	12.5	13.0	4%	13.6	13.9	2%
U10	13.0	13.4	3%	12.8	13.0	2%	13.4	13.9	4%	13.8	13.8	0%
U11	13.6	13.6	0%	13.8	13.8	0%	13.3	14.3	8%	13.0	13.2	2%
U12	13.9	14.0	1%	13.6	14.2	4%	13.3	13.5	2%	13.7	13.8	1%
U13	13.4	13.4	0%	13.5	13.5	0%	13.0	13.0	0%	13.7	13.7	0%
U14	13.1	13.2	1%	13.0	13.2	2%	13.4	13.6	1%	13.2	13.3	1%
U15	13.6	13.7	1%	13.4	13.5	1%	13.3	13.7	3%	13.9	14.1	1%

Appendix AL. Electrical Resistance Data after the First 30 Drops, Zero Hour, Leg 6, Board #3 & 4.

	Leg 6						Leg 6					
	Zero hour						Zero hour					
BD#	3						4					
SIDE	A			B			A			B		
	T0	T30	%	T0	T30	%	T0	T30	%	T0	T30	%
U1	13.2	13.2	0%	13.5	13.7	1%	13.7	13.9	1%	13.0	13.1	1%
U2	13.0	13.2	2%	13.2	13.4	2%	13.7	14.0	2%	13.9	14.0	1%
U3	13.1	13.6	4%	13.5	13.7	1%	12.9	13.1	2%	12.8	13.1	2%
U4	12.4	12.7	2%	12.7	13.1	3%	12.5	13.0	4%	12.7	12.8	1%
U5	12.9	13.1	2%	13.7	13.8	1%	12.9	13.3	3%	13.2	13.3	1%
U6	12.9	13.0	1%	13.2	13.5	2%	13.8	14.0	1%	13.8	14.0	1%
U7	12.5	13.0	4%	13.6	13.7	1%	13.2	13.2	0%	13.2	13.2	0%
U8	13.6	13.8	1%	13.9	14.0	1%	13.5	13.6	1%	13.5	13.6	1%
U9	13.3	13.9	5%	13.4	13.6	1%	13.1	13.2	1%	13.6	13.6	0%
U10	13.9	14.0	1%	12.6	12.9	2%	13.3	13.5	2%	13.5	13.5	0%
U11	13.5	13.6	1%	13.1	13.8	5%	13.5	13.5	0%	13.4	13.8	3%
U12	13.8	13.8	0%	13.2	13.8	5%	13.2	13.3	1%	13.4	13.8	3%
U13	13.2	13.2	0%	13.3	13.1	-2%	13.2	13.5	2%	13.1	13.1	0%
U14	12.8	13.0	2%	12.6	12.8	2%	13.5	13.5	0%	13.5	13.5	0%
U15	13.6	13.6	0%	13.4	13.8	3%	13.6	13.7	1%	13.6	13.9	2%

Appendix AM. Electrical Resistance Data after the First 30 Drops, HTS500, Leg 6, Board #1 & 2.

	Leg 6						Leg 6					
	HTS500						HTS500					
BD#	1						2					
SIDE	A			B			A			B		
	T0	T30	%	T0	T30	%	T0	T30	%	T0	T30	%
U1	13.8	14.0	1%	13.8	14.0	1%	13.3	13.4	1%	13.4	13.5	1%
U2	13.2	13.5	2%	13.5	13.7	1%	14.2	14.3	1%	13.8	14.0	1%
U3	13.2	13.6	3%	12.6	12.7	1%	13.1	13.4	2%	12.8	13.0	2%
U4	12.7	13.0	2%	13.2	13.5	2%	13.3	13.6	2%	13.3	13.3	0%
U5	13.1	13.6	4%	13.8	14.0	1%	13.1	13.2	1%	13.3	14.0	5%
U6	13.5	13.5	0%	13.6	13.7	1%	13.3	13.3	0%	13.6	13.6	0%
U7	14.0	14.0	0%	13.5	13.8	2%	14.0	14.1	1%	13.2	13.2	0%
U8	13.5	13.7	1%	13.9	14.1	1%	13.1	13.2	1%	12.7	12.9	2%
U9	12.0	12.6	5%	13.5	13.5	0%	13.4	13.4	0%	13.8	14.1	2%
U10	13.7	13.9	1%	13.3	13.9	5%	13.5	13.7	1%	13.6	13.6	0%
U11	13.7	13.7	0%	13.4	13.6	1%	13.0	13.1	1%	13.4	13.5	1%
U12	12.8	13.0	2%	13.9	14.2	2%	13.9	13.9	0%	13.5	13.6	1%
U13	13.1	13.1	0%	13.3	13.5	2%	13.7	14.0	2%	13.3	13.6	2%
U14	13.5	13.6	1%	13.6	13.6	0%	13.8	13.8	0%	13.6	13.9	2%
U15	13.8	13.8	0%	13.9	14.0	1%	13.6	13.7	1%	13.3	13.4	1%

Appendix AN. Electrical Resistance Data after the First 30 Drops, HTS500, Leg 6, Board #3 & 4.

	Leg 6						Leg 6					
	HTS500						HTS500					
BD#	3						4					
SIDE	A			B			A			B		
	T0	T30	%	T0	T30	%	T0	T30	%	T0	T30	%
U1	13.0	13.2	2%	13.7	13.7	0%	13.5	13.8	2%	13.1	13.2	1%
U2	13.9	14.0	1%	12.9	13.2	2%	13.9	14.0	1%	13.7	13.9	1%
U3	12.8	13.0	2%	13.1	13.7	5%	12.6	12.6	0%	12.6	13.0	3%
U4	14.0	14.1	1%	13.6	14.0	3%	13.2	13.4	2%	13.2	13.5	2%
U5	12.8	13.2	3%	13.6	14.0	3%	13.1	13.4	2%	13.7	14.0	2%
U6	13.0	13.4	3%	13.9	14.1	1%	13.5	13.6	1%	13.5	13.9	3%
U7	13.8	13.9	1%	13.6	13.7	1%	13.2	13.7	4%	14.0	14.2	1%
U8	13.9	13.9	0%	14.1	14.3	1%	13.4	13.9	4%	13.8	14.1	2%
U9	13.2	13.4	2%	13.5	13.7	1%	13.0	13.4	3%	13.5	13.5	0%
U10	12.9	13.5	5%	13.0	13.0	0%	13.8	13.8	0%	13.3	13.5	2%
U11	13.8	14.0	1%	13.8	14.0	1%	13.2	13.5	2%	13.7	13.8	1%
U12	13.6	13.9	2%	13.8	13.8	0%	13.7	14.0	2%	12.9	13.0	1%
U13	13.4	13.4	0%	13.6	13.7	1%	13.3	13.3	0%	13.2	13.2	0%
U14	13.5	13.8	2%	13.9	14.0	1%	12.8	13.0	2%	13.3	13.7	3%
U15	13.3	13.5	2%	12.8	13.1	2%	13.5	13.6	1%	13.9	14.0	1%

Appendix AO. Electrical Resistance Data after the First 30 Drops, HTS1000, Leg 6, Board #1 & 2.

	Leg 6						Leg 6					
	HTS1000						HTS1000					
BD#	1						2					
SIDE	A			B			A			B		
	T0	T30	%	T0	T30	%	T0	T30	%	T0	T30	%
U1	12.9	13.0	1%	12.9	13.2	2%	13.0	13.1	1%	12.6	13.9	10%
U2	13.3	13.3	0%	12.2	12.6	3%	13.3	13.6	2%	13.9	14.1	1%
U3	13.8	14.0	1%	13.0	13.3	2%	13.9	14.1	1%	13.0	13.2	2%
U4	13.7	13.8	1%	12.7	13.0	2%	13.0	13.2	2%	12.7	13.0	2%
U5	14.0	14.1	1%	13.4	13.7	2%	12.7	13.0	2%	13.2	13.3	1%
U6	13.0	13.5	4%	12.6	13.1	4%	13.3	13.5	2%	12.9	13.5	5%
U7	13.5	13.5	0%	13.0	13.2	2%	13.1	13.3	2%	12.1	12.6	4%
U8	13.1	13.2	1%	13.3	13.7	3%	13.5	13.5	0%	12.4	12.9	4%
U9	13.3	13.2	-1%	13.5	13.7	1%	12.7	13.0	2%	13.4	13.4	0%
U10	13.4	13.5	1%	12.9	13.1	2%	13.6	13.9	2%	13.6	13.9	2%
U11	12.8	12.9	1%	13.3	13.5	2%	13.3	13.5	2%	13.9	14.2	2%
U12	13.8	13.9	1%	13.7	14.0	2%	12.9	13.2	2%	13.0	13.5	4%
U13	13.8	14.0	1%	12.7	13.2	4%	13.0	13.4	3%	12.6	13.0	3%
U14	13.1	13.1	0%	13.4	13.5	1%	12.1	12.6	4%	13.4	13.6	1%
U15	12.8	13.2	3%	12.6	13.0	3%	13.7	13.9	1%	13.3	13.7	3%

Appendix AP. Electrical Resistance Data after the First 30 Drops, HTS1000, Leg 6, Board #3 & 4.

	Leg 6						Leg 6					
	HTS1000						HTS1000					
BD#	3						4					
SIDE	A			B			A			B		
	T0	T30	%	T0	T30	%	T0	T30	%	T0	T30	%
U1	12.4	12.4	0%	13.7	13.9	1%	13.1	13.1	0%	13.6	13.8	1%
U2	13.8	14.1	2%	12.6	12.8	2%	12.6	13.0	3%	13.1	13.3	2%
U3	13.6	13.8	1%	13.5	13.6	1%	13.3	13.5	2%	13.3	13.7	3%
U4	13.3	13.5	2%	13.5	13.5	0%	13.9	14.1	1%	13.7	14.0	2%
U5	12.9	13.3	3%	13.4	13.6	1%	13.5	13.5	0%	13.5	13.5	0%
U6	13.2	13.6	3%	13.7	14.0	2%	13.4	13.7	2%	13.8	14.1	2%
U7	13.6	13.8	1%	12.8	13.2	3%	13.0	13.3	2%	13.0	13.6	5%
U8	12.6	12.9	2%	13.3	13.5	2%	13.3	13.8	4%	13.1	13.7	5%
U9	13.0	13.4	3%	13.0	13.4	3%	13.7	13.7	0%	13.4	13.4	0%
U10	12.8	13.0	2%	13.9	14.2	2%	13.8	13.9	1%	13.9	14.0	1%
U11	13.3	13.5	2%	13.6	13.8	1%	13.1	13.4	2%	13.5	13.7	1%
U12	13.5	13.9	3%	13.7	13.9	1%	13.7	14.0	2%	13.2	13.2	0%
U13	13.2	13.6	3%	12.5	12.8	2%	12.8	13.2	3%	12.9	13.0	1%
U14	13.0	13.0	0%	12.2	12.4	2%	12.9	13.0	1%	13.1	13.5	3%
U15	13.6	13.8	1%	13.2	13.2	0%	13.6	13.8	1%	13.7	13.8	1%

Appendix AQ. Electrical Resistance Data after the First 30 Drops, Zero Hour, Leg 7, Board #1 & 2.

	Leg 7						Leg 7					
	Zero hour						Zero hour					
BD#	1						2					
SIDE	A			B			A			B		
	T0	T30	%	T0	T30	%	T0	T30	%	T0	T30	%
U1	13.7	13.9	1%	13.0	13.2	2%	13.4	13.5	1%	13.3	13.4	1%
U2	13.6	13.8	1%	13.5	13.8	2%	13.9	14.3	3%	13.8	13.8	0%
U3	13.5	13.8	2%	13.2	13.6	3%	13.6	14.0	3%	14.2	14.2	0%
U4	13.7	14.2	4%	13.3	13.4	1%	13.7	13.7	0%	13.6	13.6	0%
U5	13.3	13.4	1%	13.9	14.0	1%	13.3	13.7	3%	13.5	13.8	2%
U6	13.7	13.8	1%	13.2	13.9	5%	13.6	13.7	1%	14.0	14.2	1%
U7	13.9	13.9	0%	13.7	13.8	1%	13.1	13.5	3%	13.6	13.6	0%
U8	13.7	13.9	1%	13.3	13.6	2%	13.7	13.9	1%	13.8	14.0	1%
U9	13.7	14.0	2%	13.6	13.7	1%	14.0	14.0	0%	13.8	13.9	1%
U10	13.7	13.8	1%	13.2	13.2	0%	13.6	13.7	1%	13.6	13.8	1%
U11	13.0	13.1	1%	13.4	13.4	0%	14.0	14.0	0%	13.5	13.9	3%
U12	13.7	13.7	0%	13.2	13.5	2%	13.8	13.9	1%	13.9	13.9	0%
U13	13.3	13.8	4%	14.0	14.4	3%	14.0	14.3	2%	13.6	13.9	2%
U14	13.7	13.8	1%	13.6	13.6	0%	14.0	14.2	1%	13.7	14.0	2%
U15	13.8	13.9	1%	13.4	13.7	2%	13.8	13.8	0%	14.0	14.0	0%

Appendix AR. Electrical Resistance Data after the First 30 Drops, Zero Hour, Leg 7, Board #3 & 4.

	Leg 7						Leg 7					
	Zero hour						Zero hour					
BD#	3						4					
SIDE	A			B			A			B		
	T0	T30	%	T0	T30	%	T0	T30	%	T0	T30	%
U1	12.9	13.2	2%	13.7	14.0	2%	13.1	13.8	5%	13.3	13.5	2%
U2	13.4	13.8	3%	13.6	13.6	0%	13.0	13.6	5%	13.2	13.4	2%
U3	13.8	13.8	0%	14.0	14.1	1%	14.1	14.3	1%	13.0	13.0	0%
U4	13.2	13.4	2%	13.7	13.8	1%	13.1	13.2	1%	13.3	13.6	2%
U5	14.1	14.1	0%	13.4	13.5	1%	12.8	12.9	1%	13.9	14.0	1%
U6	13.6	13.8	1%	13.5	13.9	3%	12.7	13.5	6%	13.3	13.3	0%
U7	13.2	13.3	1%	12.7	13.0	2%	12.9	13.5	5%	13.5	13.5	0%
U8	13.4	13.7	2%	14.1	14.2	1%	13.5	13.9	3%	13.3	13.9	5%
U9	13.4	13.4	0%	13.1	13.1	0%	13.2	13.3	1%	13.2	13.5	2%
U10	13.2	13.4	2%	12.9	13.0	1%	12.1	12.2	1%	13.2	13.4	2%
U11	13.1	13.9	6%	13.4	13.6	1%	12.6	12.8	2%	13.6	13.9	2%
U12	13.5	13.6	1%	13.6	13.7	1%	12.8	13.0	2%	13.3	13.7	3%
U13	14.2	14.5	2%	14.6	14.7	1%	13.8	13.9	1%	13.9	14.2	2%
U14	13.3	13.6	2%	13.5	14.0	4%	13.7	14.3	4%	14.3	14.4	1%
U15	14.0	14.1	1%	13.3	14.0	5%	13.9	14.1	1%	13.4	13.6	1%

Appendix AS. Electrical Resistance Data after the First 30 Drops, HTS500, Leg 7, Board #1 & 2.

	Leg 7						Leg 7					
	HTS500						HTS500					
BD#	1						2					
SIDE	A			B			A			B		
	T0	T30	%	T0	T30	%	T0	T30	%	T0	T30	%
U1	13.4	13.6	1%	13.0	13.1	1%	14.1	14.2	1%	13.8	13.8	0%
U2	13.2	13.5	2%	13.5	13.9	3%	13.6	13.8	1%	13.0	13.4	3%
U3	13.7	13.7	0%	13.6	14.0	3%	13.4	13.4	0%	13.6	13.7	1%
U4	13.2	13.3	1%	13.4	13.9	4%	13.5	14.0	4%	12.2	12.5	2%
U5	12.8	13.1	2%	13.5	13.5	0%	13.7	13.9	1%	12.9	13.5	5%
U6	13.1	13.6	4%	12.6	12.8	2%	13.8	13.9	1%	13.2	13.2	0%
U7	12.8	13.1	2%	13.0	13.0	0%	13.0	13.7	5%	12.8	13.3	4%
U8	12.6	13.0	3%	13.4	13.6	1%	13.1	13.4	2%	13.1	13.8	5%
U9	12.9	13.0	1%	13.6	13.6	0%	13.9	14.3	3%	13.9	14.3	3%
U10	13.3	13.7	3%	13.8	14.2	3%	13.5	13.5	0%	12.9	13.5	5%
U11	13.5	13.6	1%	12.9	13.0	1%	13.5	13.6	1%	12.9	13.0	1%
U12	13.3	13.6	2%	12.7	12.9	2%	13.1	13.1	0%	12.8	13.1	2%
U13	13.4	13.4	0%	13.7	13.7	0%	13.5	14.0	4%	14.2	14.4	1%
U14	13.9	14.1	1%	13.4	13.4	0%	13.9	13.9	0%	13.9	13.9	0%
U15	14.2	14.3	1%	13.3	13.6	2%	14.0	14.4	3%	12.5	13.2	6%

Appendix AT. Electrical Resistance Data after the First 30 Drops, HTS500, Leg 7, Board #3 & 4.

	Leg 7						Leg 7					
	HTS500						HTS500					
BD#	3						4					
SIDE	A			B			A			B		
	T0	T30	%	T0	T30	%	T0	T30	%	T0	T30	%
U1	14.0	14.2	1%	13.2	13.7	4%	13.5	13.5	0%	13.0	13.1	1%
U2	13.2	13.2	0%	13.0	13.4	3%	13.6	14.1	4%	13.5	13.6	1%
U3	13.7	13.7	0%	13.1	13.6	4%	13.7	14.2	4%	13.8	13.8	0%
U4	13.8	13.8	0%	14.0	14.3	2%	13.9	14.0	1%	13.0	13.4	3%
U5	14.0	14.4	3%	13.2	13.2	0%	13.6	13.7	1%	13.1	13.5	3%
U6	13.1	13.3	2%	13.8	13.8	0%	13.2	13.2	0%	13.6	13.7	1%
U7	13.3	13.7	3%	14.1	14.4	2%	13.3	13.4	1%	13.2	13.2	0%
U8	13.4	13.4	0%	13.8	13.9	1%	14.0	14.4	3%	13.1	13.1	0%
U9	14.2	14.3	1%	13.2	13.6	3%	13.9	14.0	1%	12.6	13.1	4%
U10	13.8	13.9	1%	14.1	14.3	1%	12.8	13.5	5%	13.1	13.8	5%
U11	13.5	13.8	2%	13.7	13.8	1%	13.4	13.7	2%	13.8	13.8	0%
U12	13.4	13.6	1%	13.9	14.3	3%	13.5	13.7	1%	13.9	14.1	1%
U13	13.0	13.2	2%	13.2	13.5	2%	14.2	14.3	1%	13.4	13.7	2%
U14	13.4	13.8	3%	13.4	13.6	1%	13.0	13.2	2%	13.3	13.7	3%
U15	13.5	13.5	0%	13.1	13.6	4%	14.1	14.2	1%	14.0	14.5	4%

Appendix AU. Electrical Resistance Data after the First 30 Drops, HTS1000, Leg 7, Board #1 & 2.

	Leg 7						Leg 7					
	HTS1000						HTS1000					
BD#	1						2					
SIDE	A			B			A			B		
	T0	T30	%	T0	T30	%	T0	T30	%	T0	T30	%
U1	13.3	13.5	2%	13.5	13.5	0%	13.8	13.8	0%	13.6	13.7	1%
U2	12.7	12.8	1%	13.3	13.7	3%	13.7	13.9	1%	13.1	13.4	2%
U3	13.6	13.8	1%	13.2	13.4	2%	14.0	14.5	4%	14.0	14.3	2%
U4	13.4	13.7	2%	14.1	14.4	2%	13.2	13.3	1%	13.8	13.8	0%
U5	13.9	13.9	0%	13.3	35.7	168%	13.9	14.0	1%	13.7	13.7	0%
U6	12.8	13.0	2%	14.2	14.2	0%	13.6	13.6	0%	13.4	13.8	3%
U7	13.0	13.2	2%	13.5	13.9	3%	13.7	13.8	1%	13.6	13.6	0%
U8	13.6	13.8	1%	13.6	13.8	1%	13.8	14.1	2%	13.8	45.7	231%
U9	13.9	13.9	0%	12.7	13.0	2%	13.5	13.6	1%	13.6	13.8	1%
U10	14.3	14.4	1%	13.7	13.9	1%	14.1	14.3	1%	13.9	14.2	2%
U11	13.7	13.8	1%	13.5	14.0	4%	13.9	13.9	0%	14.3	14.4	1%
U12	12.9	13.2	2%	13.4	13.4	0%	13.4	13.4	0%	13.2	13.6	3%
U13	13.4	13.7	2%	13.8	14.1	2%	13.8	14.0	1%	13.1	13.4	2%
U14	12.8	13.0	2%	12.4	12.8	3%	12.8	13.5	5%	13.6	13.7	1%
U15	12.5	13.2	6%	13.1	13.1	0%	13.1	13.1	0%	13.5	65.2	383%

Appendix AV. Electrical Resistance Data after the First 30 Drops, HTS1000, Leg 7, Board #3 & 4.

	Leg 7						Leg 7					
	HTS1000						HTS1000					
BD#	3						4					
SIDE	A			B			A			B		
	T0	T30	%	T0	T30	%	T0	T30	%	T0	T30	%
U1	14.2	14.3	1%	13.5	14.1	4%	13.9	14.0	1%	13.9	13.9	0%
U2	13.4	13.6	1%	12.9	13.4	4%	13.3	13.5	2%	13.7	14.0	2%
U3	13.9	14.0	1%	13.8	14.0	1%	13.6	13.7	1%	13.2	13.3	1%
U4	12.5	12.9	3%	13.6	13.9	2%	13.9	13.9	0%	13.4	13.5	1%
U5	13.2	13.2	0%	14.1	14.3	1%	13.7	13.9	1%	13.3	13.8	4%
U6	14.0	14.0	0%	13.0	13.8	6%	14.2	14.5	2%	12.5	13.0	4%
U7	13.7	13.7	0%	13.2	13.5	2%	13.2	13.8	5%	13.3	13.3	0%
U8	14.2	14.5	2%	14.2	14.2	0%	13.8	14.3	4%	13.5	14.0	4%
U9	13.6	14.0	3%	13.3	13.3	0%	13.2	13.3	1%	14.2	14.4	1%
U10	12.7	13.4	6%	14.1	14.2	1%	14.0	14.0	0%	13.3	13.3	0%
U11	13.7	13.9	1%	13.5	13.8	2%	14.3	14.4	1%	13.1	13.4	2%
U12	13.6	14.0	3%	13.0	13.1	1%	13.5	13.9	3%	13.3	13.3	0%
U13	13.4	13.7	2%	13.4	13.6	1%	13.1	13.1	0%	13.1	29.6	126%
U14	12.0	12.4	3%	12.4	12.9	4%	12.9	13.0	1%	13.7	13.7	0%
U15	12.7	12.7	0%	13.7	14.0	2%	13.0	13.0	0%	12.9	13.0	1%