Drop Test Reliability of Lead-free Chip Scale Packages

Andrew Farris, Jianbiao Pan, Ph.D., Albert Liddicoat, Ph.D.
California Polytechnic State University at San Luis Obispo

Brian J. Toleno, Ph.D., Dan Maslyk
Henkel Corporation

Dongkai Shangguan, Ph.D., Jasbir Bath, Dennis Willie,
David A. Geiger
Flextronics International

Agenda

- Introduction
- Test Vehicle Design and Assembly
- Failure Detection Systems
- Reliability Data
- Local Acceleration on Component Location
- Conclusions

Prior Work

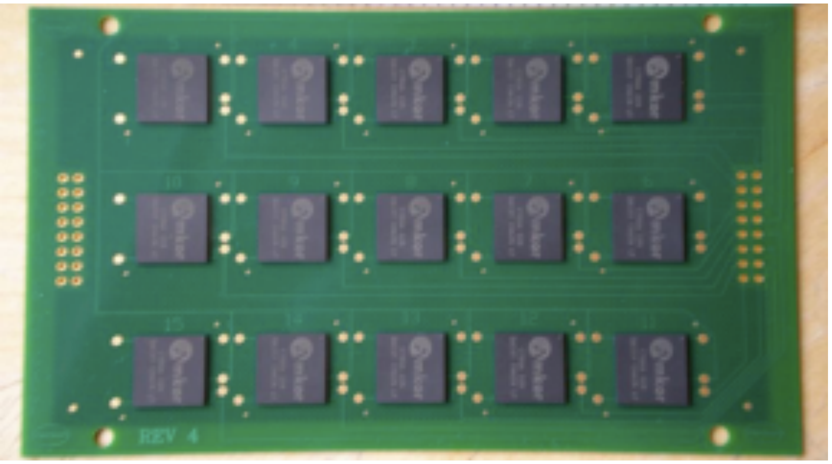
- Lead-free SnAgCu solders with various alloy additives (Syed 2006, Pandher 2007) and low-silver content (Lai 2005, Kim 2007) have been studied to improve drop impact reliability of solder joints
- Underfills (Zhang 2003, Toleno 2007) and corner bonding (Tian 2005) have been used to improve drop impact reliability

Purpose of this Study

- Compare the drop impact reliability of lead-free Chip Scale Package (CSP) solder joints, as determined by two different failure detection systems
    - In-situ data acquisition based dynamic resistance measurement
    - Static post-drop resistance measurement
- Determine the effects of edge bonding on CSP drop impact performance
- Further investigate the failure mechanisms of drop impact failures in lead-free CSPs under JEDEC drop impact test conditions

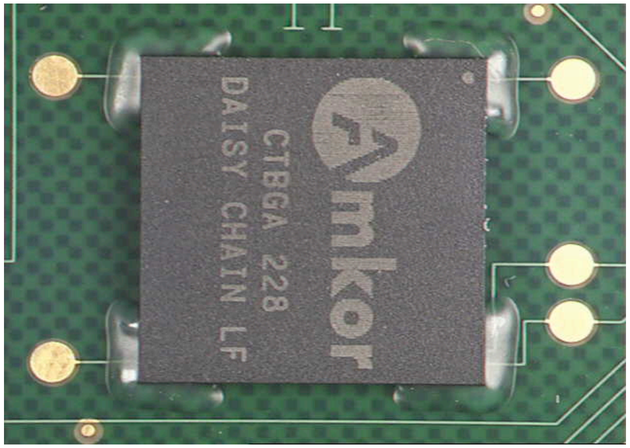
Test Vehicle

- JEDEC JESD22-B111 preferred board, 8-layer FR4, 132 mm x 77 mm x 1mm, OSP finish
- Amkor 12mm x 12mm CSPs, 228 I/Os, 0.5mm pitch, SAC305 solder bumps
- Multicore 318 LF 97SC (SAC305) solder paste

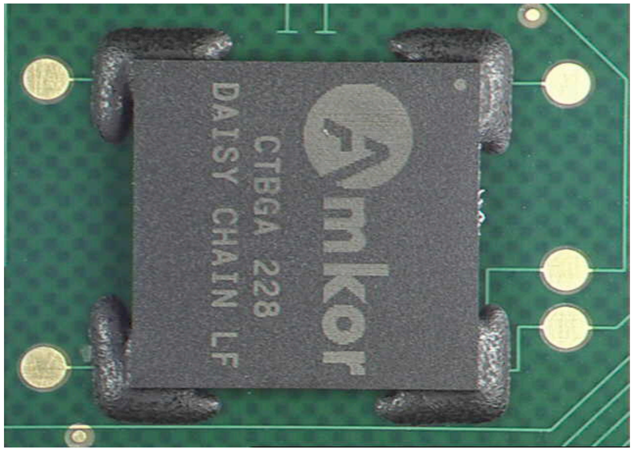


Edge Bond Materials

- Edge bonding 12mm CSPs
  - Acrylated Urethane material
    - Cured by UV exposure for 80s using Zeta 7411 Lamp
  - Epoxy material
    - Thermally cured for 20min in 80° C oven



Acrylic



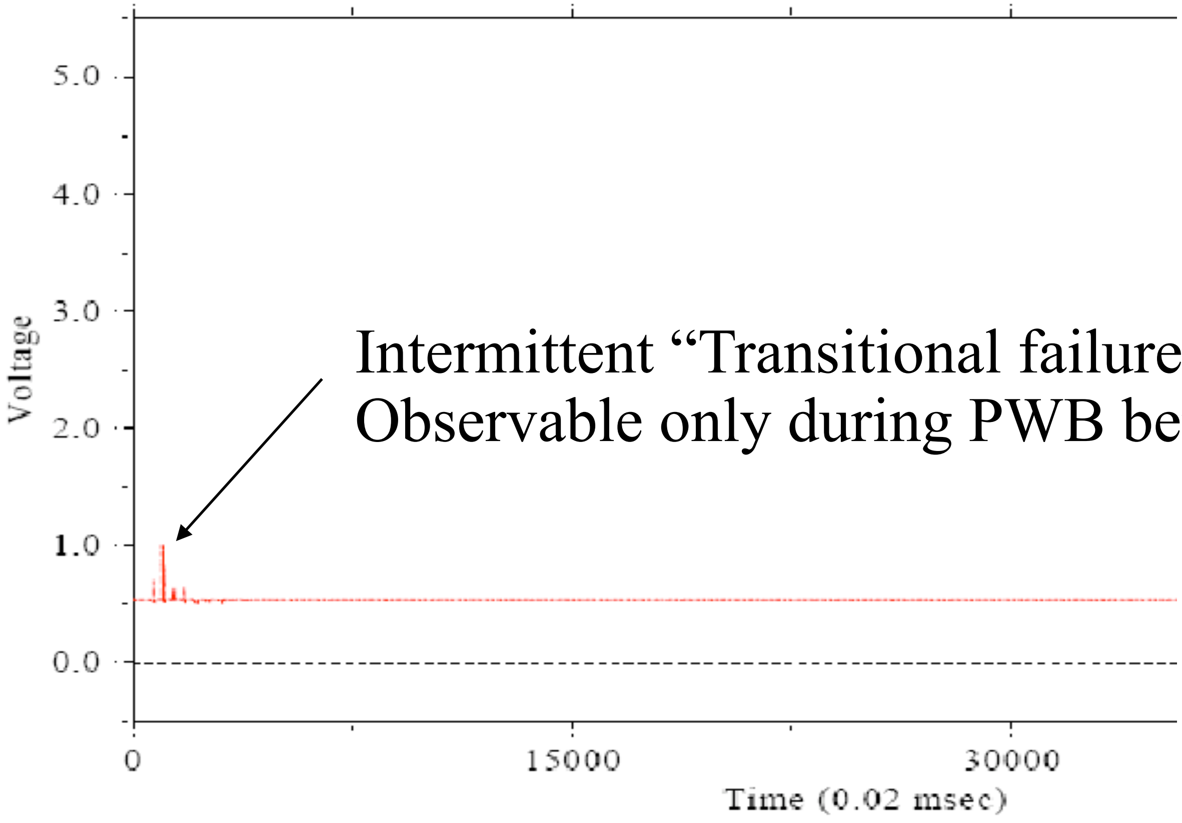
Epoxy

Failure Detection Systems

- Compare two failure detection systems
  - In-situ dynamic resistance measurement by data acquisition (DAQ)
    - Uses voltage divider circuit to relate voltage to resistance, and analog-to-digital conversion at 50kHz
  - Post-drop static resistance measurement
    - Single resistance measurement taken after the drop

Failure Event

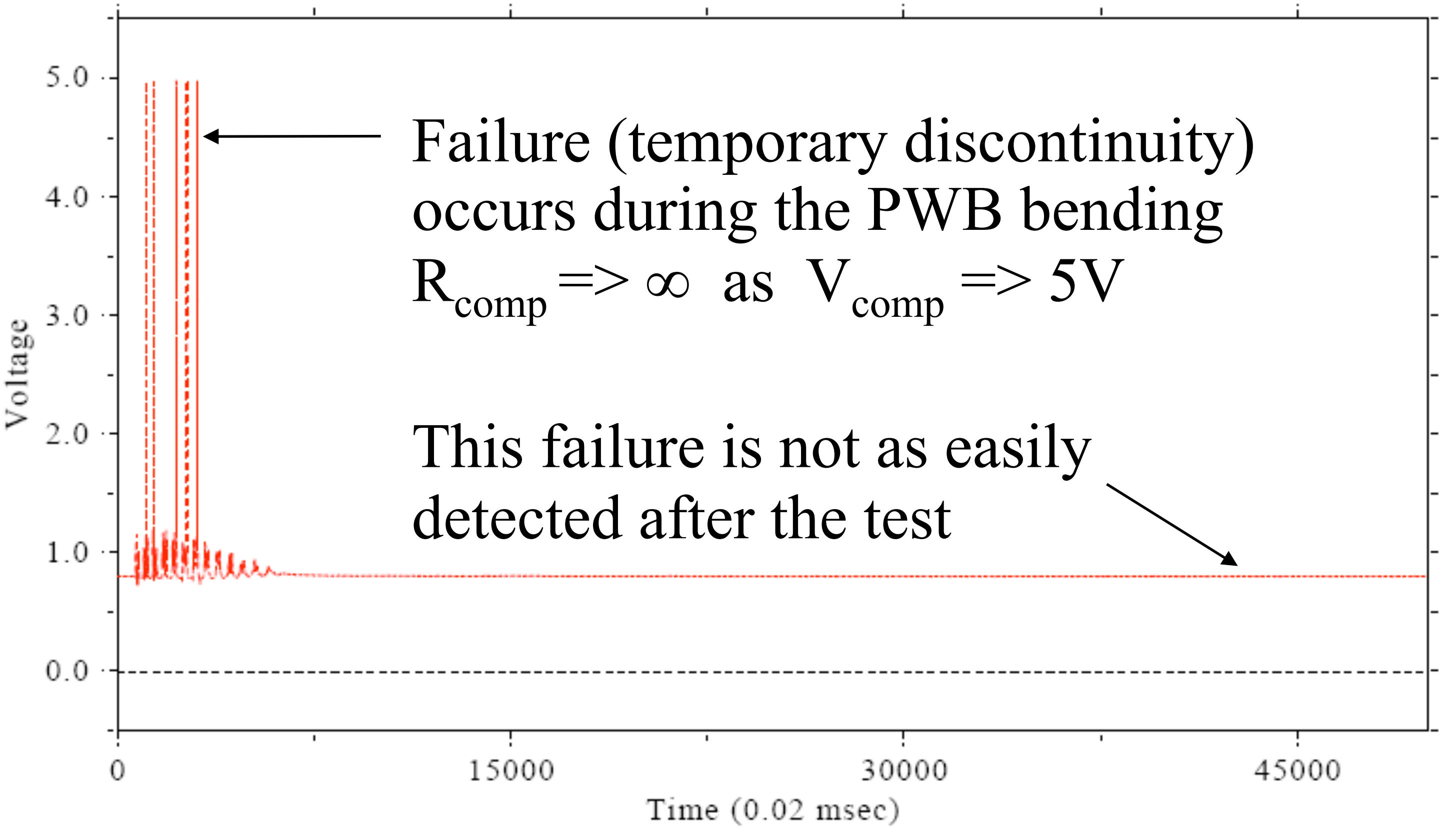
- Display results plot: sampled voltage vs time



Intermittent “Transitional failure”
Observable only during PWB bending

Failure Event

- Display results plot: sampled voltage vs time



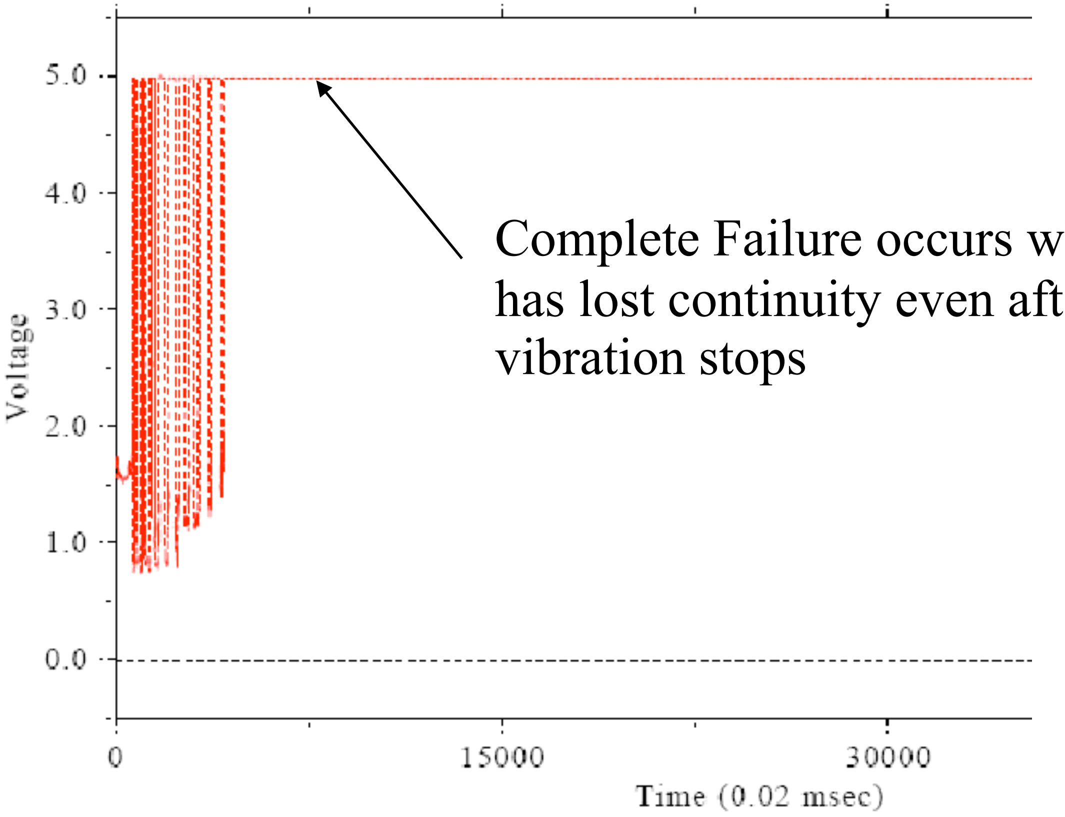
Failure (temporary discontinuity) occurs during the PWB bending

$R_{comp} \Rightarrow \infty$ as $V_{comp} \Rightarrow 5V$

This failure is not as easily detected after the test

Failure Event

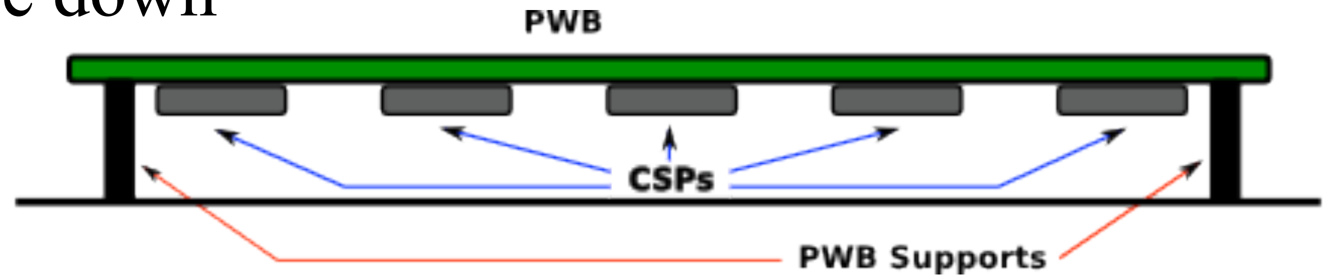
- Display results plot: sampled voltage vs time



Complete Failure occurs when the daisy-chain has lost continuity even after the PWB vibration stops

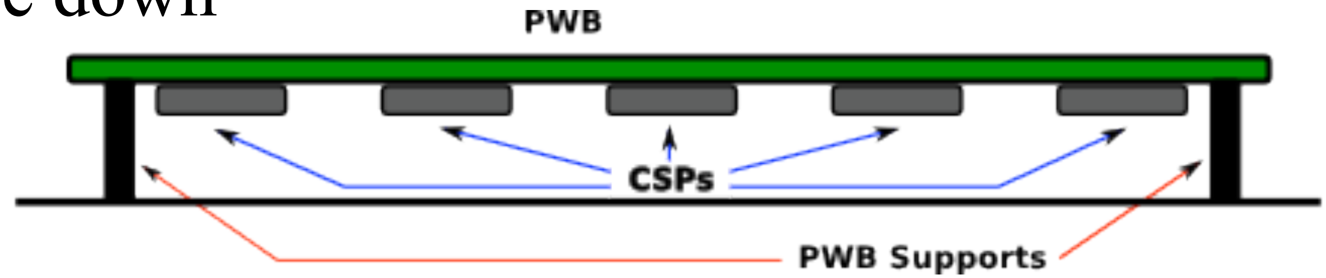
Test Vehicle Drop Orientation

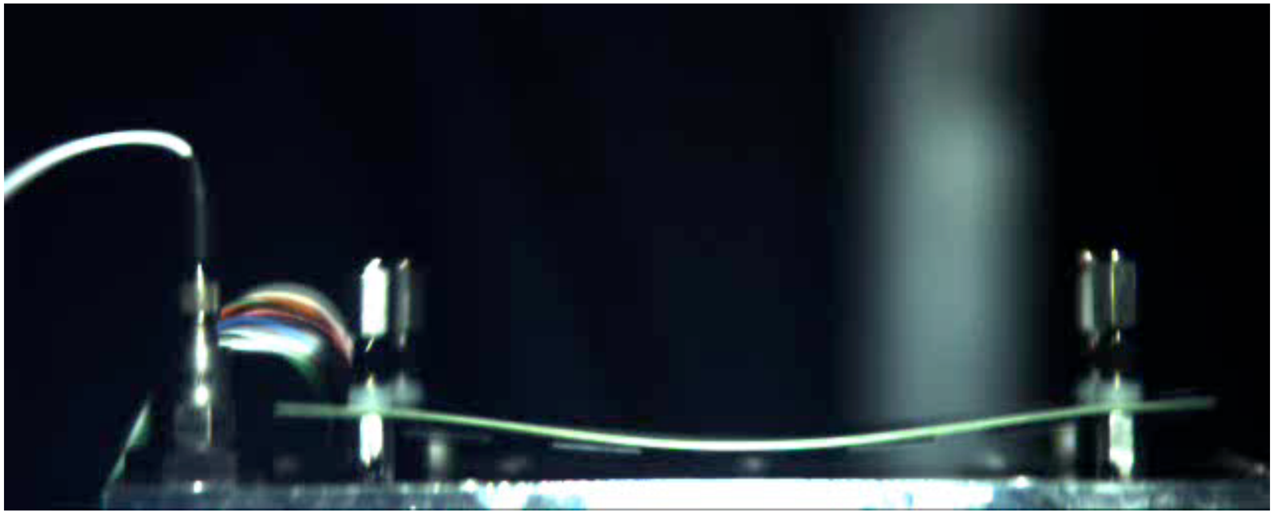
- Test vehicle is always mounted with components face down



Test Vehicle Drop Orientation

- Test vehicle is always mounted with components face down





Agenda

- Introduction
- Test Vehicle Design and Assembly
- Failure Detection Systems
- <u>Reliability Data</u>
- Local Acceleration on Component Location
- Conclusions

Reliability Test Design

- Two failure detection systems
- Three acceleration conditions
- Edge-bonded and not edge-bonded CSPs

Failure Detection	**DAQ System**		**Post-Drop System**	
Edge-bonding	Yes	No	Yes	No
900 G – 0.7 ms	0	3	0	3
1500 G – 0.5 ms	4	3	4	3
2900 G – 0.3 ms	4	1	4	0

Component Locations

- JEDEC defined component numbering
  - Our DAQ cable always attaches near component 6, on the short end of the board

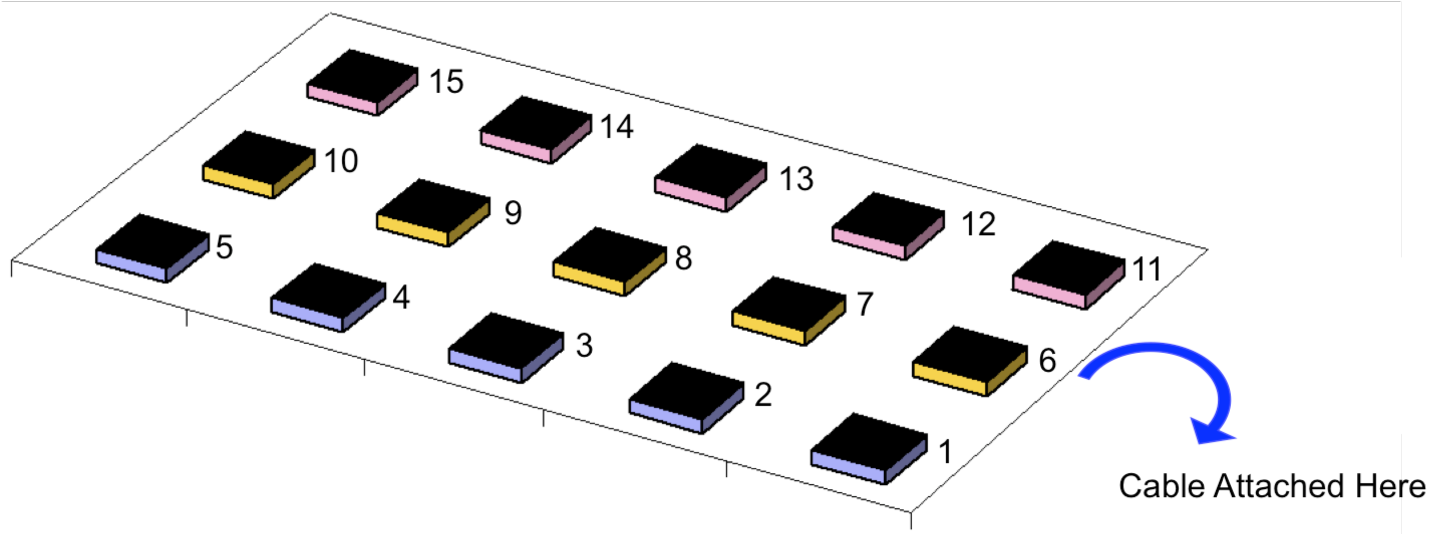


Table 2 - DAQ No Edge-bond

Accel (g)	900	900	900	1500	1500	1500	2900
Drops	75	75	100	70	40	60	50
Edge Bond	None	None	None	None	None	None	None
Component							
C1				**37**	**29**		**7**
C2							**25**
C3	**62**				**14**	**33**	**4**
C4	**26**	**26**	**34**	**26**	**6**	**23**	**4**
C5							**5**
C6					**21**	**35**	**3**
C7					**19**		**42**
C8	**28**	**44**		**50**	**3**	**13**	**7**
C9					**30**		**21**
C10							
C11					**5**		**11**
C12	**16**	**6**	**43**	**13**	**2**	**6**	**4**
C13	**15**	**11**	**40**	**9**	**1**	**5**	**2**
C14					**21**	**32**	**38**
C15							**50**

Table 3 - Post-drop No Edge-bond

Accel (g)	900	900	900	1500	1500	1500
Drops	75	70	100	70	40	60
Edge Bond	None	None	None	None	None	None
Component						
C1			**82**	**55**		**38**
C2						**22**
C3	**7**	**31**	**15**	**8**	**3**	**11**
C4	**10**	**43**	**17**	**7**	**5**	**36**
C5	**65**	**2**	**14**	**1**	**5**	**14**
C6	**54**					**45**
C7			**61**			**9**
C8	**13**	**13**	**16**	**7**	**5**	**2**
C9	**53**	**16**	**11**	**28**	**8**	**14**
C10						
C11	**29**		**55**			**12**
C12	**6**	**9**	**18**	**5**	**3**	**3**
C13	**5**	**28**	**16**	**5**	**3**	**3**
C14	**1**		**37**	**5**	**34**	**4**
C15	**44**		**75**	**26**		

Table 4 - DAQ with Edge-bond

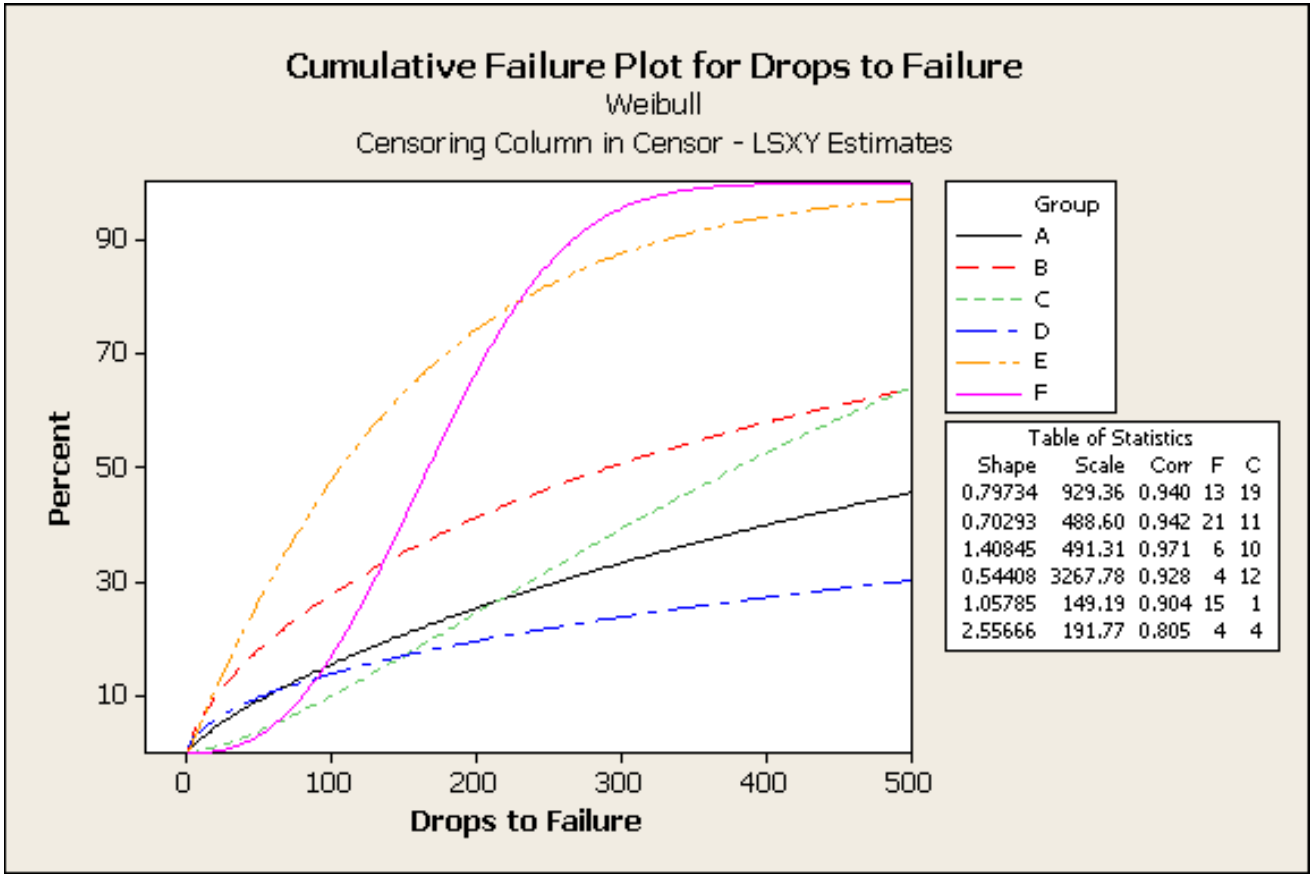
Accel (g)	1500	1500	1500	1500	2900	2900	2900	2900
Drops	325	350	279	355	190	170	175	173
Edge Bond	Heat	Heat	UV	UV	Heat	Heat	UV	UV
Component								
C1						**151**	**66**	**61**
C2		**342**	**276**		**133**	**127**		**119**
C3	**80**	**292**	**33**	**101**	**70**	**72**	**12**	**103**
C4	**236**	**255**	**257**		**63**	**16**		**100**
C5						**36**	**73**	**91**
C6		**55**				**44**	**37**	**60**
C7						**35**	**69**	**158**
C8	**201**			**85**	**113**	**20**	**84**	**83**
C9				**292**		**25**	**29**	**124**
C10			**277**			**12**	**59**	
C11		**193**	**178**	**103**		**65**	**38**	
C12	**66**	**76**	**52**	**162**	**53**	**24**	**23**	**16**
C13	**61**	**129**	**73**	**77**	**42**	**13**	**18**	**14**
C14		**232**				**42**	**44**	**120**
C15	**107**		**268**		**44**	**22**	**25**	**90**

Table 5 - Post-drop with Edge-bond

Accel (g)	1500	1500	1500	1500	2900	2900	2900	2900
Drops	237	350	279	300	170	170	175	173
Edge Bond	Heat	Heat	UV	UV	Heat	Heat	UV	UV
Component								
C1		**304**	**62**			**12**	**23**	
C2			**101**				**34**	**98**
C3	**2**		**180**	**81**	**74**	**72**		**23**
C4	**2**	**292**	**99**	**242**		**25**	**13**	
C5	**60**		**62**	**262**		**40**		**151**
C6	**112**	**282**	**180**			**151**		
C7		**6**						
C8	**88**			**108**		**68**	**30**	**21**
C9		**132**		**283**	**116**	**106**	**53**	
C10		**112**						
C11	**3**	**292**				**112**		
C12	**1**	**36**	**188**	**162**	**137**	**57**	**154**	**128**
C13	**159**	**99**	**188**	**133**	**6**	**144**	**36**	**43**
C14	**60**			**243**			**151**	
C15				**297**				

Cumulative Failure Plot by Group– 1500g

- Groups E and F show significantly faster failure rates



Cumulative Failure Plot for Drops to Failure
Weibull
Censoring Column in Censor - LSXY Estimates

Table of Statistics

Shape	Scale	Corr	F	C
0.79734	929.36	0.940	13	19
0.70293	488.60	0.942	21	11
1.40845	491.31	0.971	6	10
0.54408	3267.78	0.928	4	12
1.05785	149.19	0.904	15	1
2.55666	191.77	0.805	4	4

Cumulative Failure Plot by Group – 2900g

- 2900g data has more failures – more consistent plots

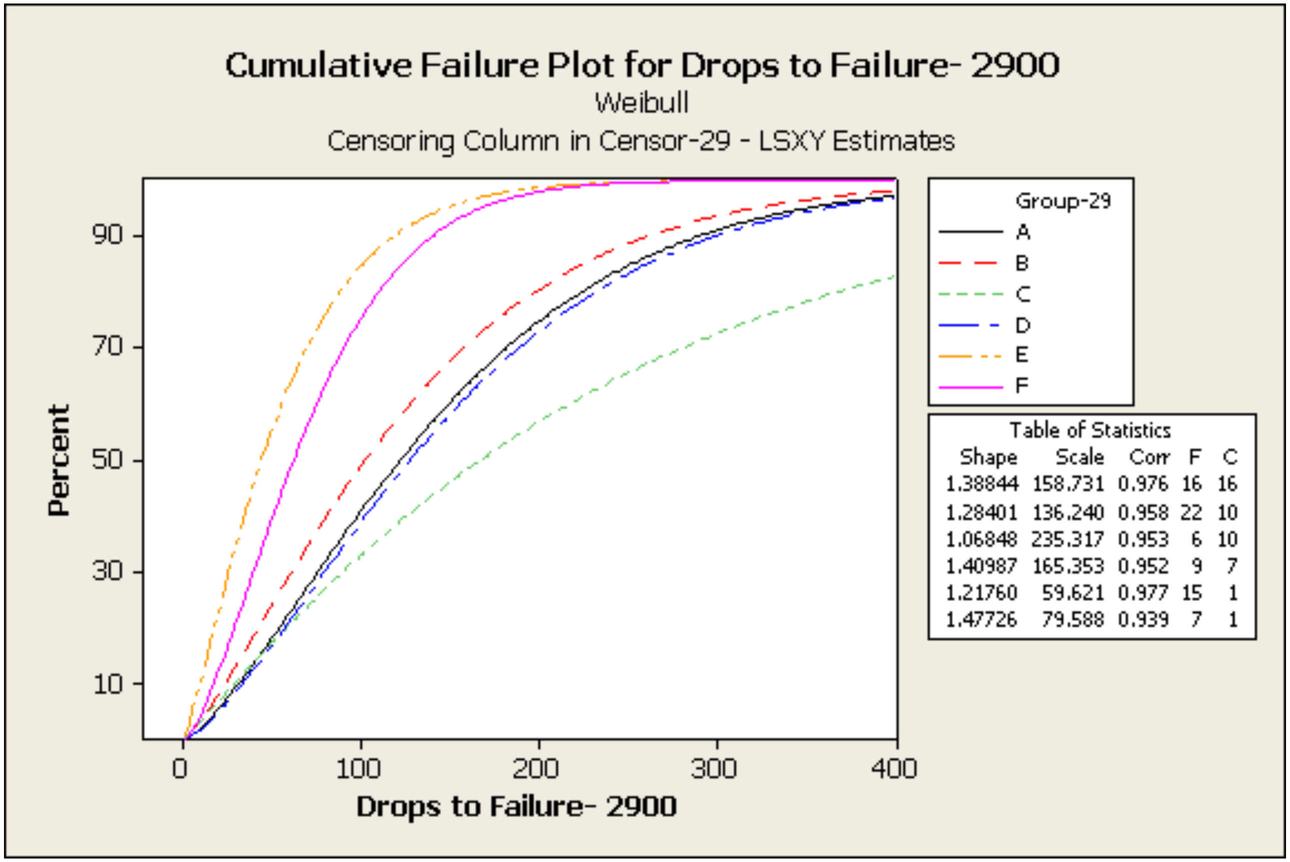


Table of Statistics

Shape	Scale	Corr	F	C
1.38844	158.731	0.976	16	16
1.28401	136.240	0.958	22	10
1.06848	235.317	0.953	6	10
1.40987	165.353	0.952	9	7
1.21760	59.621	0.977	15	1
1.47726	79.588	0.939	7	1

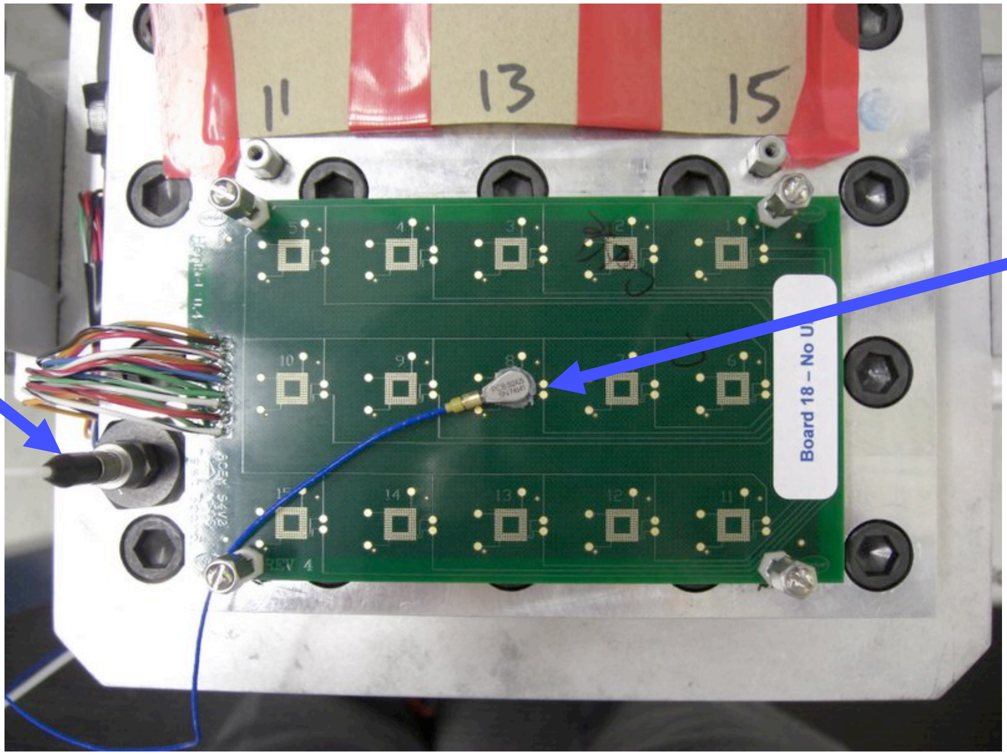
Cable Influence on PWB Loading

- Results from the comparison of failure detection methods
  - The DAQ system cable attached to the PWB appears to effects loading conditions
  - Fewer components fell off the DAQ tested boards than off the post-drop tested boards
  - The earliest component failure locations vary between DAQ and post-drop tested boards

Agenda

- Introduction
- Test Vehicle Design and Assembly
- Failure Detection Systems
- Reliability Data
- <u>Local Acceleration on Component Location</u>
- Conclusions

Local Acceleration Conditions



Testing the acceleration condition on the board and table simultaneously

Local Acceleration Conditions

- Table baseplate has insignificant vibration
- Board vibrates over period longer than 10ms

Accelerometer
on Drop Table
(red channel)

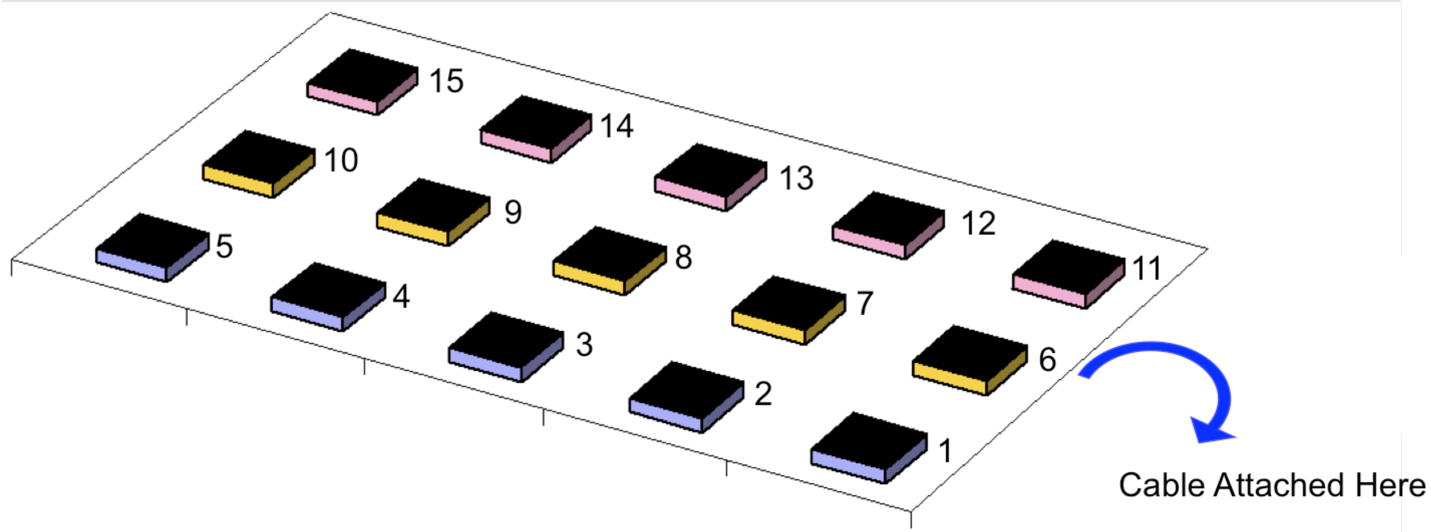
Acceleration vs Time

		Channel Description:	G's	msec	In/S	Filter Hz	Max G's	Min G's
Ch1	🟥	Channel 1	1538.81	0.48	157.25	5000.00	1538.81	-44.09
Ch2	🟩	Channel 2	3834.61	0.20	185.80	5000.00	3834.61	-2172.47

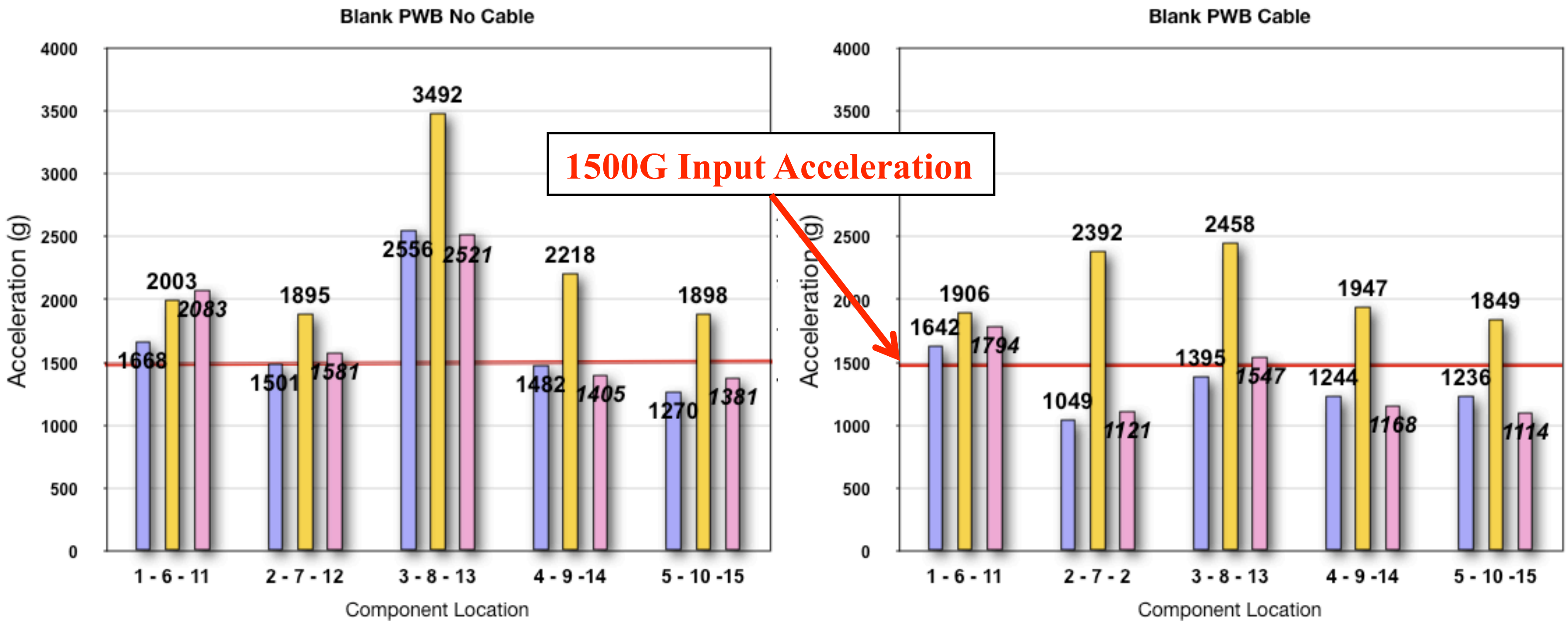
Accelerometer
above
Component C8
(green channel)

Component Locations

- JEDEC defined component numbering
  - The DAQ cable attaches near component C6 (in between components C1 and C11)

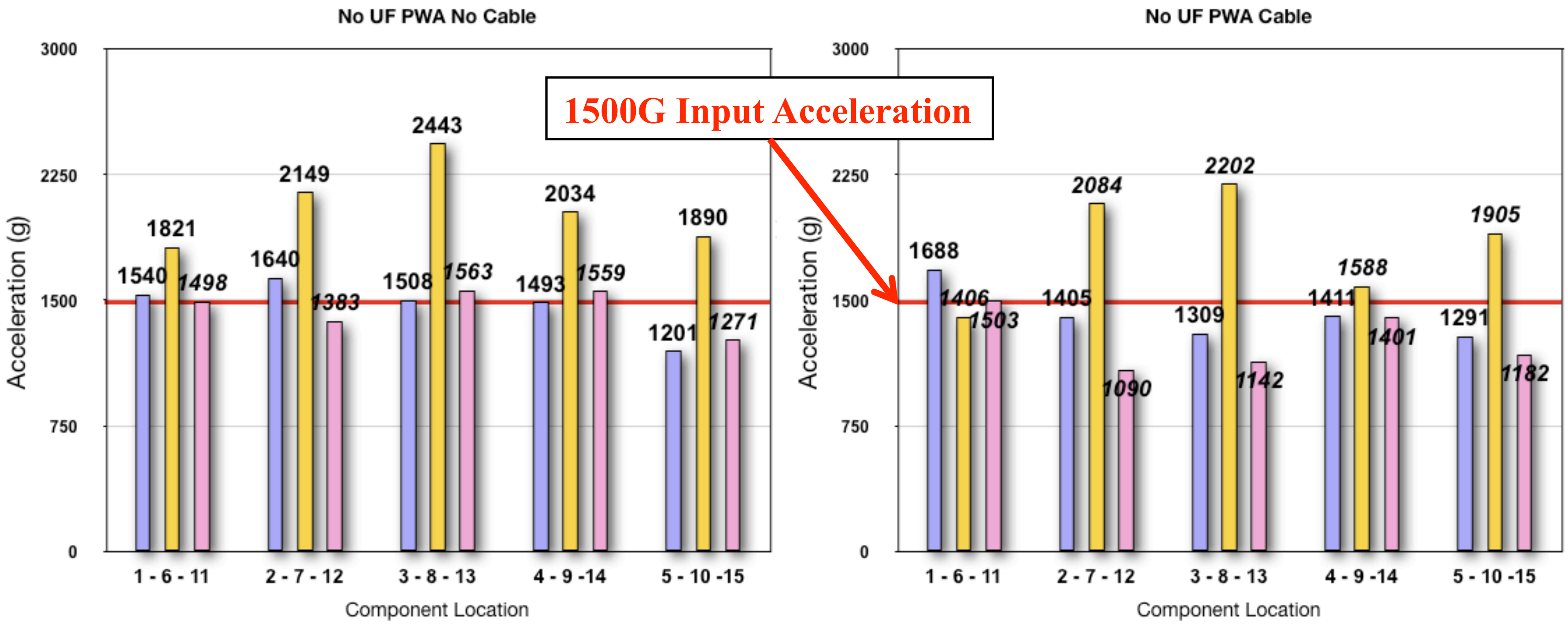


Blank PWB – No Cable vs Cable



- Symmetry of acceleration peaks has shifted (C7 vs C9)
- Maximums greatly reduced by cable (C3, C13, C8)

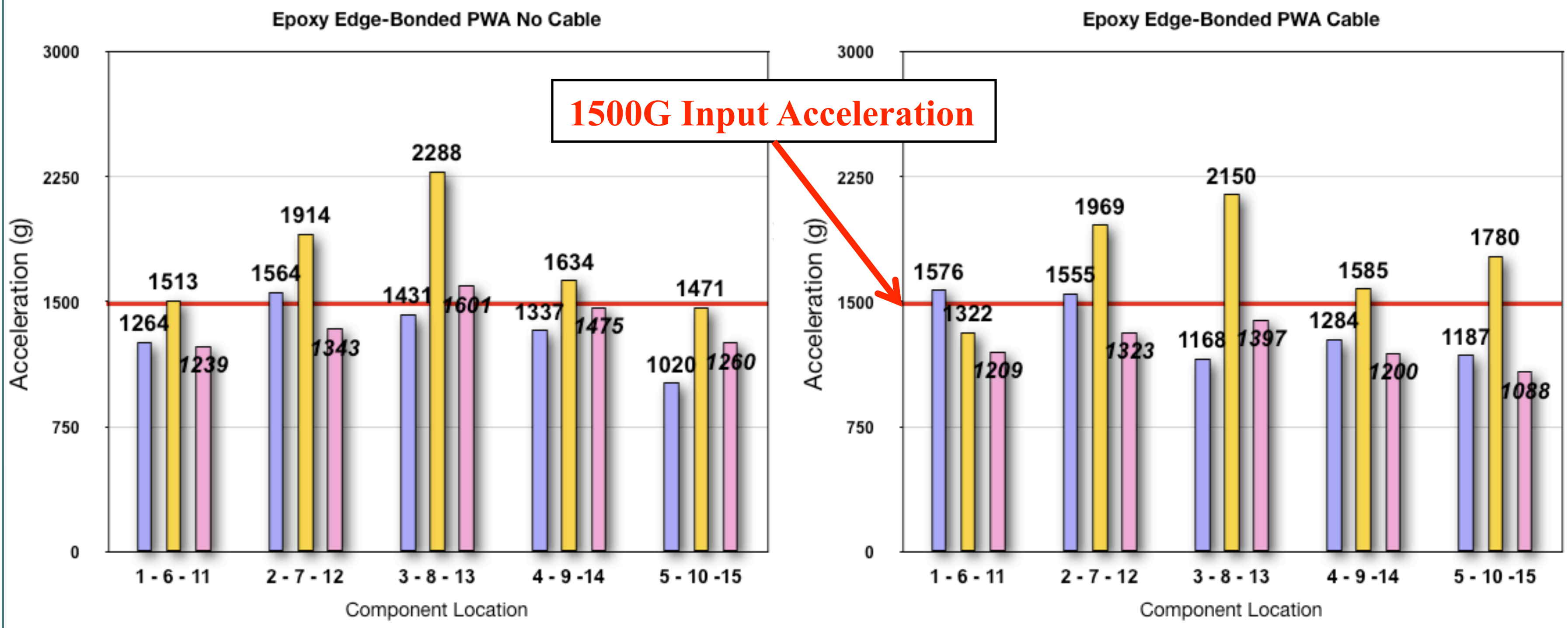
Populated PWB – No Edge Bond



1500G Input Acceleration

- Dampening due to the cable seems less significant than with blank PWB (both graphs are more similar)

Epoxy Edge Bonded CSPs

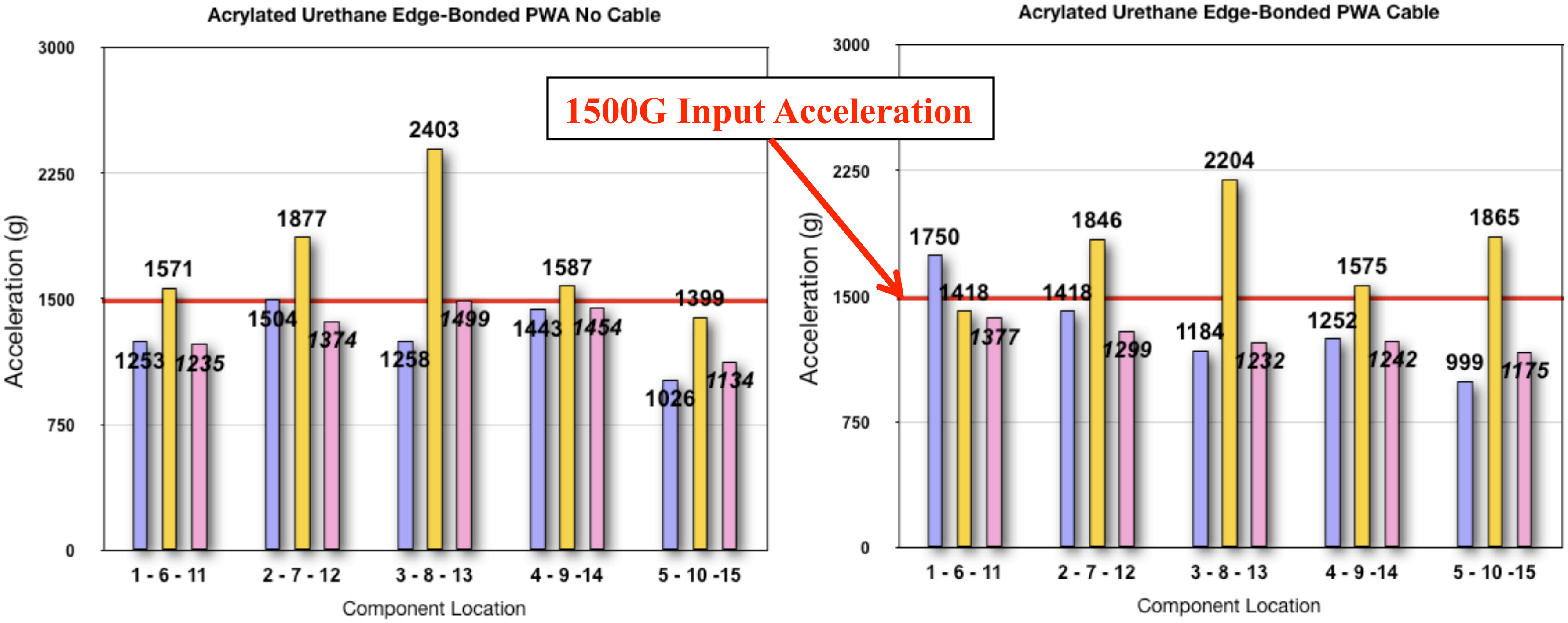

Epoxy Edge-Bonded PWA No Cable

Epoxy Edge-Bonded PWA Cable

1500G Input Acceleration

- Stiffer board with edge bonding has less symmetry disturbance
- Overall accelerations are significantly reduced vs no edge-bond

Acrylic Edge Bonded CSPs



- Stiffer board with edge bonding has less symmetry disturbance
- Overall accelerations are significantly reduced vs no edge-bond

Summary of Results

Drop test results – With Blank

Component	1	2	3	4	5
Cable Sig.	No	Yes	Yes	Yes	No
Board Pop Sig.	No	No	Yes	No	No
Interactions	No	No	Yes	No	No
Component	**6**	**7**	**8**	**9**	**10**
Cable Sig.	Yes	No	Yes	Yes	No
Board Pop Sig.	Yes	No	Yes	Yes	No
Interactions	No	No	Yes	No	No
Component	**11**	**12**	**13**	**14**	**15**
Cable Sig.	No	Yes	Yes	Yes	No
Board Pop Sig.	Yes	No	Yes	Yes	No
Interactions	No	No	No	No	No

Drop test results – Without Blank

Component	1	2	3	4	5
Cable Sig.	No	No	Yes	Yes	No
Board Pop Sig.	No	No	No	No	No
Interactions	No	No	No	No	No
Component	**6**	**7**	**8**	**9**	**10**
Cable Sig.	Yes	No	Yes	No	No
Board Pop Sig.	Yes	No	No	No	No
Interactions	Yes	No	No	No	No
Component	**11**	**12**	**13**	**14**	**15**
Cable Sig.	No	No	Yes	Yes	No
Board Pop Sig.	No	No	No	Yes	No
Interactions	No	No	No	No	No

- Red: Significant at least 95%

Conclusions

- Edge bonding significantly increases the reliability of lead-free CSPs in drop impact conditions
  - Increased drops to failure between 5x to 8x
  - The reliability increase of the two edge bond materials used did not differ significantly
- The component location on the test vehicle has a significant role in reliability
- The cable attached to the PWB has an effect on some component locations stress/strain

Supplemental Slides

Acknowledgements

- Project Sponsors:

Henkel

A Brand like a Friend

FLEXTRONICS

- Office of Naval Research (ONR)

  Through California Central Coast Research Park (C^3RP)
- Society of Manufacturing Engineers Education Foundation
- Surface Mount Technology Association San Jose Chapter

Conclusions

- Cohesive or adhesive failure between the PWB outer resin layer and the board fiberglass leads to pad cratering
- Pad cratering causes trace breakage that is the most common electrical failure mode for this specific lead-free test vehicle
- Board laminate materials are the weakest link in this lead-free test vehicle assembly, rather than the solder joints

Drop Impact Reliability

- Mobile electronic devices

  - Are prone to being dropped (or thrown)
  - Are important to our everyday activities
  - Are expected to 'just work' even after rough handling

Drop Test Reliability (cont.)

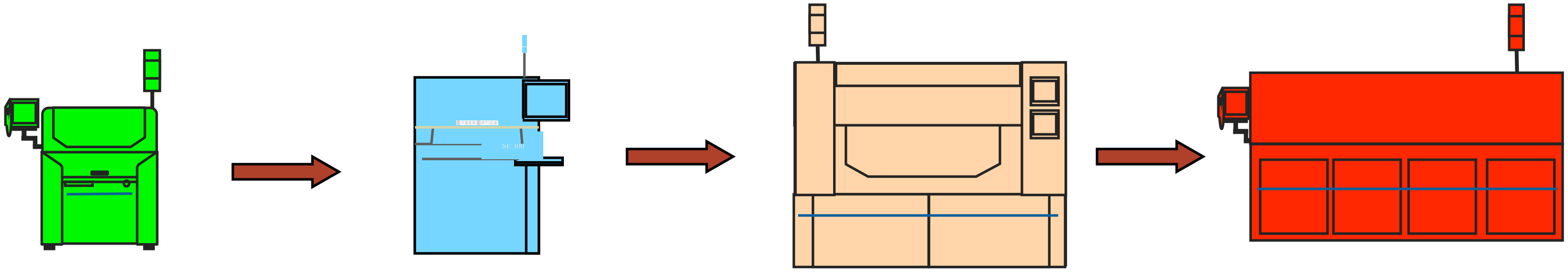
- Mobile electronic devices also…
  - Are complicated and expensive
  - Are easily damaged by drop impacts
  - Are designed to be lightweight and portable
- Drop test reliability is:
  - The study of how well a device or part survives repeated drop impacts
  - A process to determine where design improvements are needed for future high reliability designs

Drop Impact Reliability

- Drop impact reliability testing evaluates the reliability of electronics when subjected to mechanical shock
  - Shock causes PWB bending that results in mechanical stress and strain in solder joints
- Generally focused on lead-free solder usage in consumer electronics (handheld products)
  - Due to governmental regulations pushing toward a lead-free market for these products

SMT Assembly

- Dedicated lead-free SMT assembly line



DEK
Stencil
Printing

CyberOptic
Solder Paste
Inspection

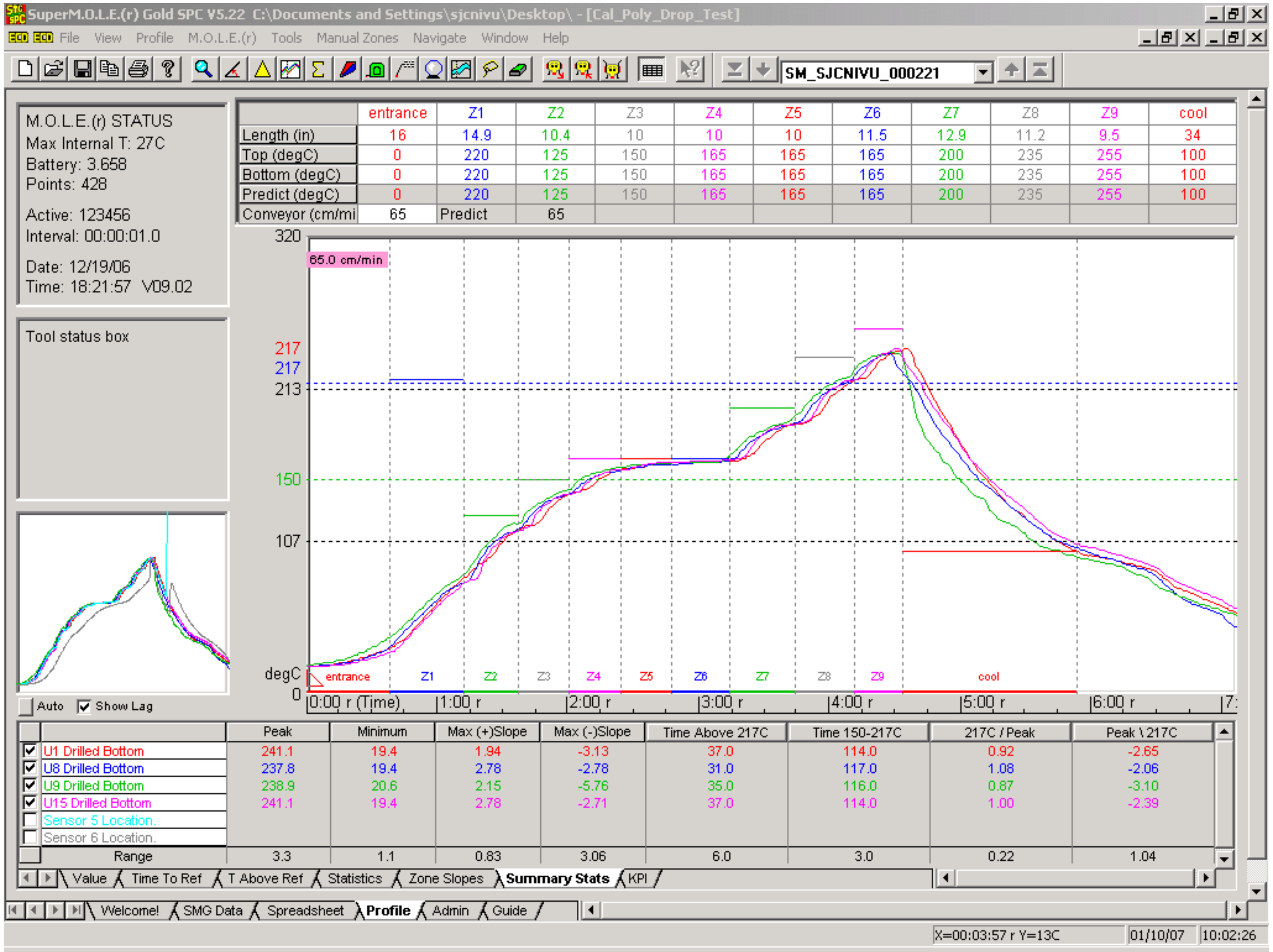
Siemens F5
Placement

Heller Oven
EXL1800

SMT Assembly (cont.)

- Stencil (DEK)
  - 4 mil thick
  - Electro-Polish
  - 12 mil square
- Stencil Printing
  - Front/Rear Speed: 40 mm/s
  - Front/Rear Pressure: 12 kg
  - Squeegee length: 300mm
  - Separation Speed: 10 mm/s

Solder Reflow Profile



M.O.L.E.(r) STATUS
Max Internal T: 27C
Battery: 3.658
Points: 428

Active: 123456
Interval: 00:00:01.0

Date: 12/19/06
Time: 18:21:57 V09.02

Tool status box

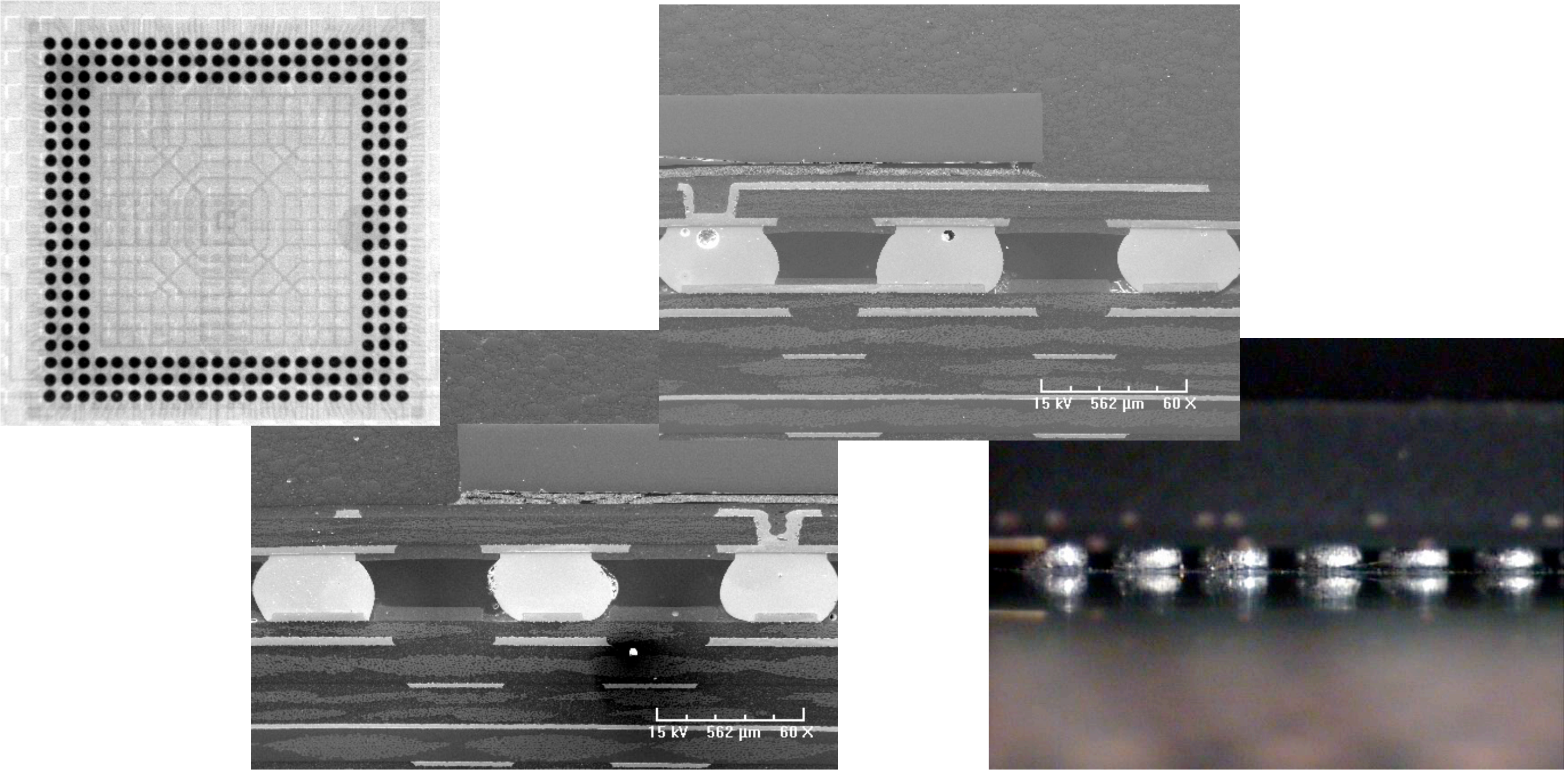
	entrance	Z1	Z2	Z3	Z4	Z5	Z6	Z7	Z8	Z9	cool
Length (in)	16	14.9	10.4	10	10	10	11.5	12.9	11.2	9.5	34
Top (degC)	0	220	125	150	165	165	165	200	235	255	100
Bottom (degC)	0	220	125	150	165	165	165	200	235	255	100
Predict (degC)	0	220	125	150	165	165	165	200	235	255	100
Conveyor (cm/mi	65	Predict	65								

	Peak	Minimum	Max (+)Slope	Max (-)Slope	Time Above 217C	Time 150-217C	217C / Peak	Peak \ 217C
☑ U1 Drilled Bottom	241.1	19.4	1.94	-3.13	37.0	114.0	0.92	-2.65
☑ U8 Drilled Bottom	237.8	19.4	2.78	-2.78	31.0	117.0	1.08	-2.06
☑ U9 Drilled Bottom	238.9	20.6	2.15	-5.76	35.0	116.0	0.87	-3.10
☑ U15 Drilled Bottom	241.1	19.4	2.78	-2.71	37.0	114.0	1.00	-2.39
☐ Sensor 5 Location.								
☐ Sensor 6 Location.								
Range	3.3	1.1	0.83	3.06	6.0	3.0	0.22	1.04

X=00:03:57 r Y=13C 01/10/07 10:02:26

Solder Joint Integrity after Assembly

- X-Ray and SEM images after assembly showed round, uniform, and well collapsed solder joints

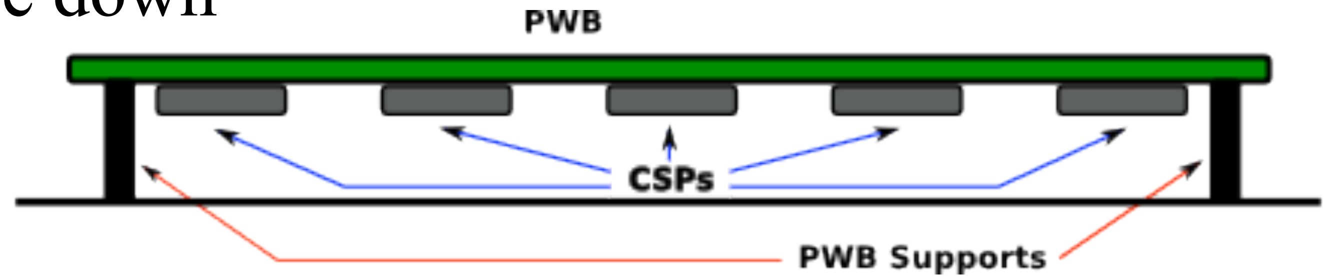


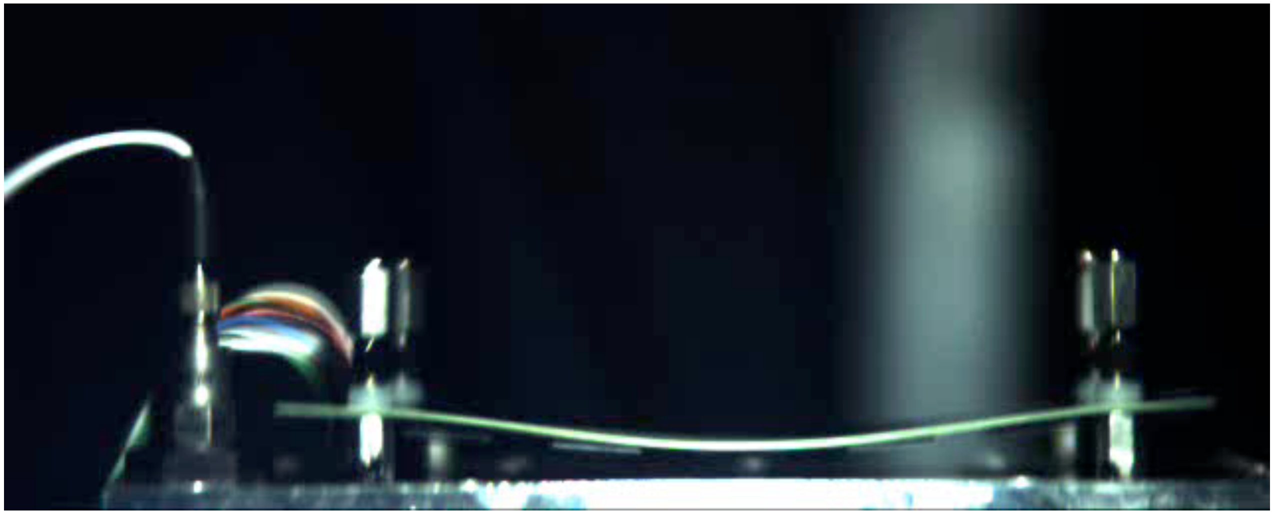
Definition: Drop Impact Failure

- Drop impact failure…
  - Occurs when the electrical connections in the device are damaged so that it no longer functions as designed
  - Is typically detected by change of resistance or loss of continuity in board level circuits
  - May be either a permanent or intermittent condition

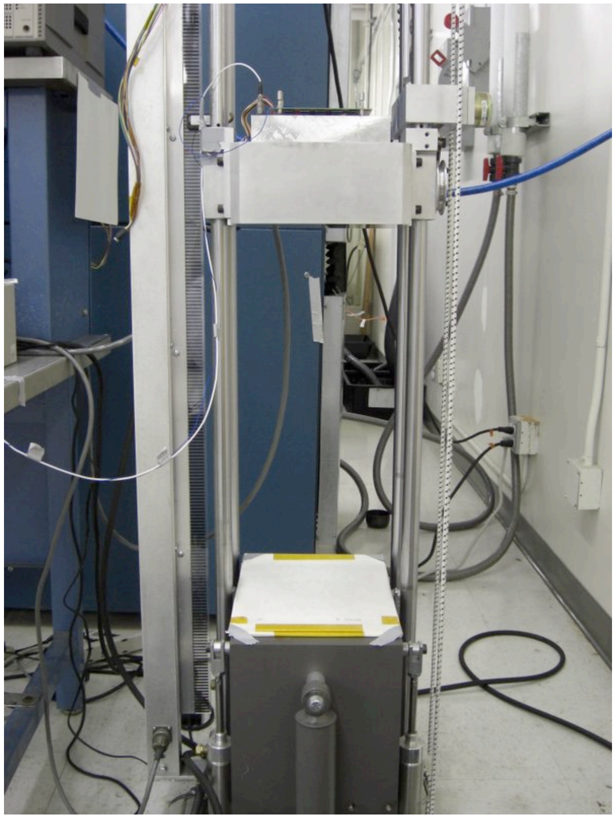
Test Vehicle Drop Orientation

- Test vehicle is always mounted with components face down



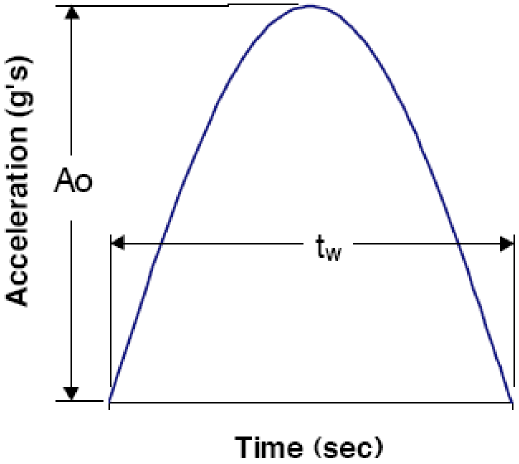


Drop Impact Input Acceleration



Lansmont MTS II Shock Tester

Typical Half-sine
Acceleration Pulse



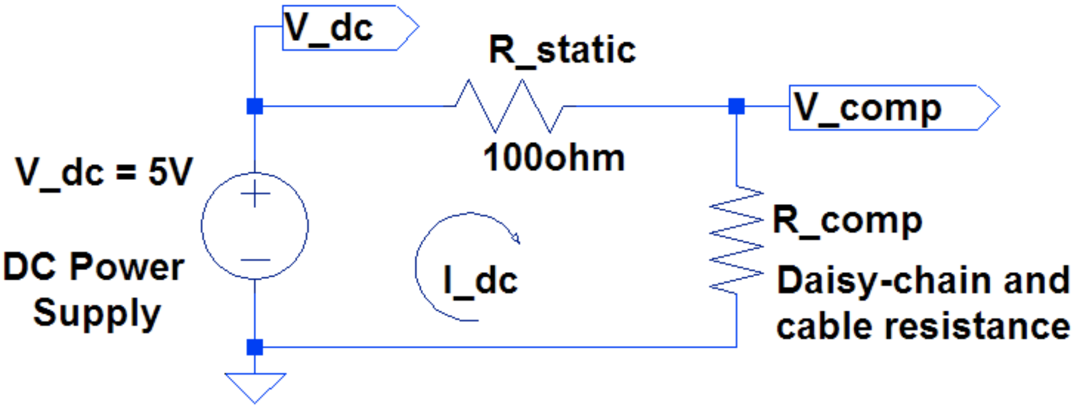
e.g. 1500g - 0.5ms
or 2900g - 0.3ms

Voltage Divider Circuit

- Dynamic resistance measurement is achieved by using a series voltage divider circuit to relate voltage to resistance (Luan 2006)

$$V_{Comp} = V_{DC} \cdot \frac{R_{Comp}}{R_{Comp} + R_{Static}}$$

$$R_{Comp} = \frac{V_{Comp} \cdot R_{Static}}{V_{DC} - V_{Comp}}$$



Data Acquisition System Summary

- DAQ system capabilities
  - 17 channels (15 for the components, 1 each for power supply voltage and trigger)
  - Sampling frequency of 50kHz per channel
    - Follows JEDEC standard recommendation
  - 16 bit measurement accuracy (over 0-5V range)
  - Store entire data set for later analysis
    - Tab-separated-text (CSV) data value tables
    - PDF format graphs of each measured channel

Post-Drop Resistance Measurement

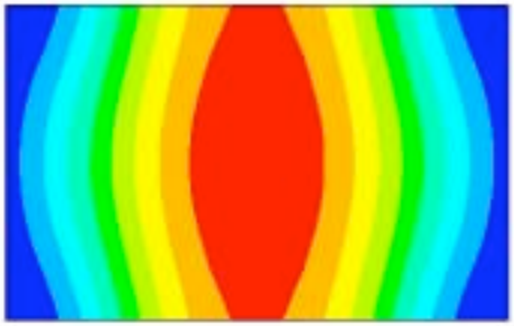
- Uses a single resistance measurement per drop, taken after the board vibration ceases
- The failure criteria is a 10 ohm static rise from nominal daisy-chain resistance

Post-Drop Resistance Measurement

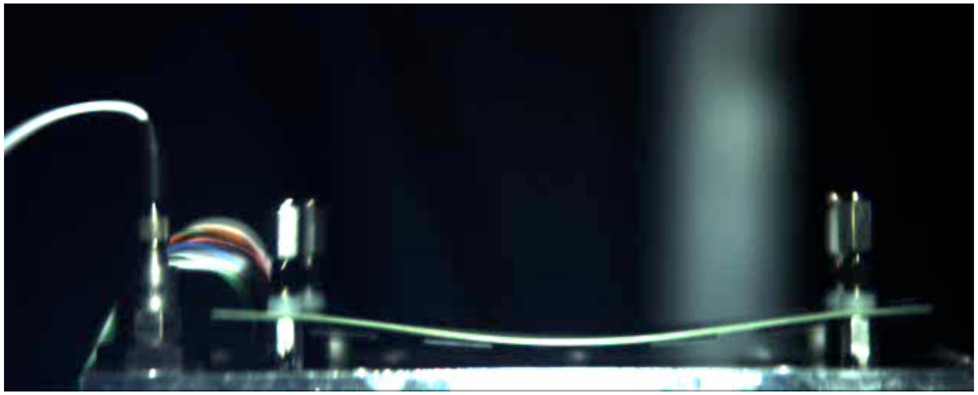
- Advantage:
  - No wires soldered to the test board, no interference with board mechanics
  - Low cost system
- Disadvantages:
  - Cannot test in-situ dynamic response (during board deflection and vibration conditions)
  - Only one test per drop provides fairly poor resolution for when failure occurs
  - Not easily automated (operator must take readings)

PWB Loading Conditions

- JEDEC drop testing causes a complex PWB strain condition; not all solder joints experience the same stress and strain
  - Reliability and failure analysis must consider component location, drop count, and acceleration pulse profile



(Image from JEDEC JESD22-B111)



Local Acceleration Conditions

- Using two accelerometers, the acceleration profile of the board at each component location was tested
- Eight board variations
  - Blank PWB, Populated, with edge bond, and without edge bond
  - With and without DAQ cable soldered into the board

Cable Influence on Acceleration

- Symmetry of acceleration/deflection/strain is effected:
  - A cable soldered to the PWB will effect the test conditions for any test vehicle assembly
  - Components cannot be grouped as liberally for reliability statistics if test conditions at their locations are not similar
- Lightest possible wire gauge should be used
  - But must provide reliable through-hole solder joints

Analytical Method - ANOVA

1. **Objective(s) of the experiment:**
- To determine the effects of an attached cable and edge bond material at each component of a JEDEC JESD22-B111 board.

2. **Response Variable(s):**
- Maximum g-force measured

3. **Factors (control variables):**
- Cable attached: A cable was either attached or not attached next to component 6
- Board Population: The type of edge bond material used for the board

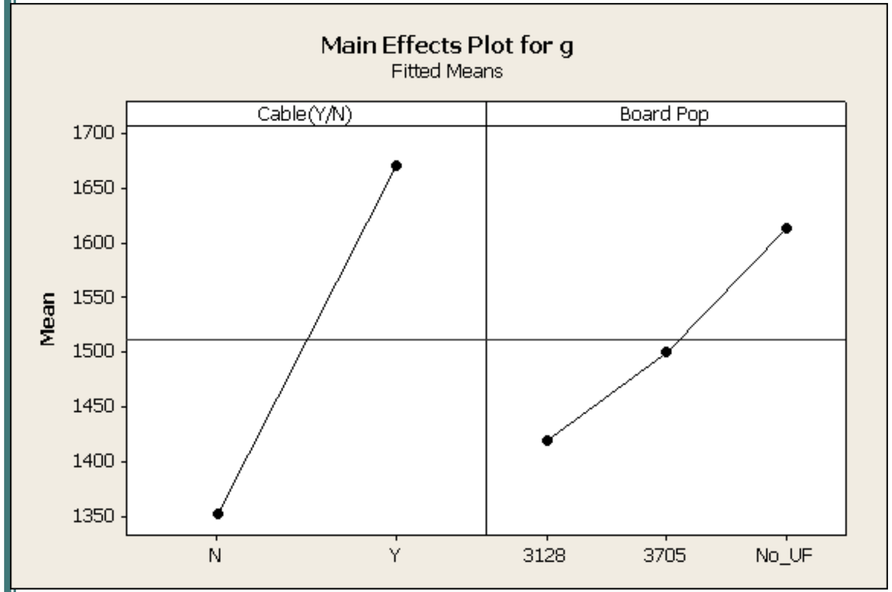
4. **Levels for each factor:**
- Cable attached: Yes or No
- Edge Bond Material: 3128, 3705, No Underfill, Blank

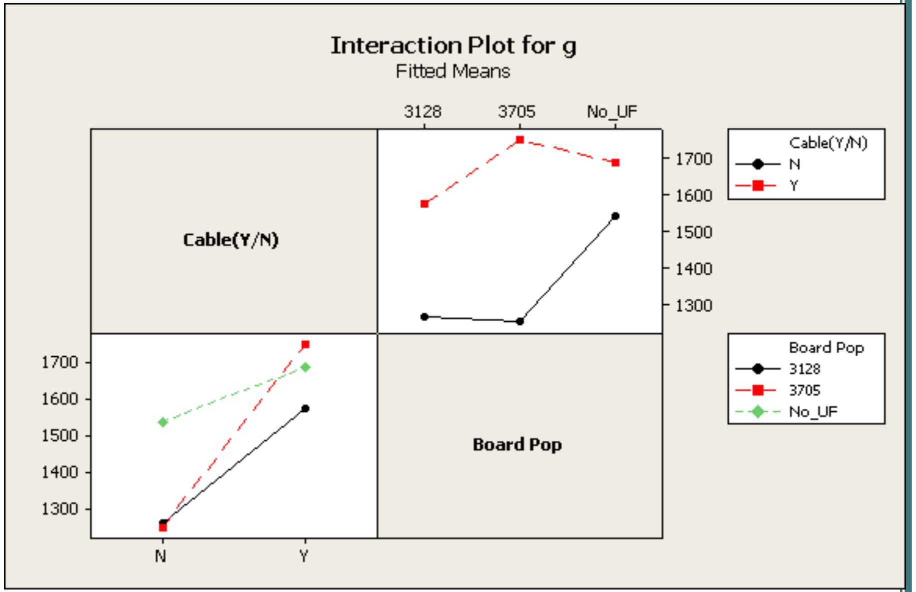
5. **Total Number of Treatment Combinations:**
- 2 x 4 = 8 Combinations

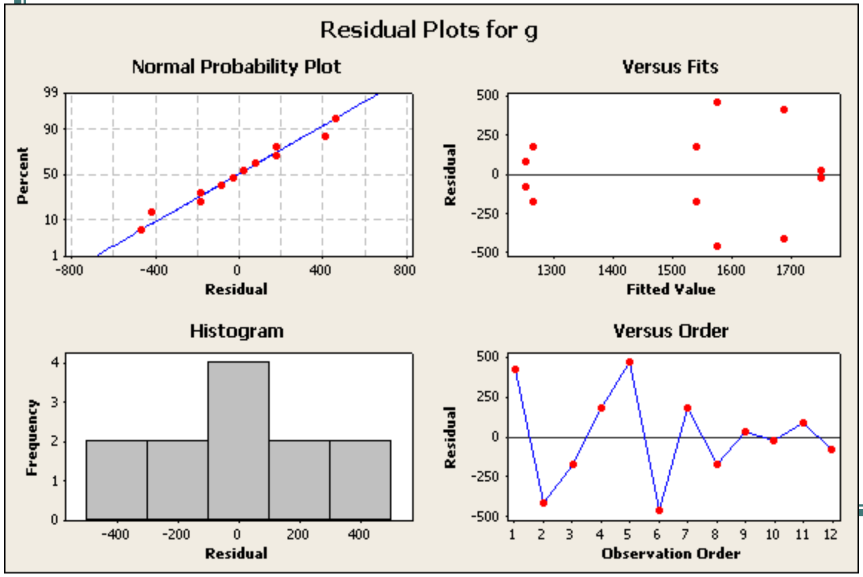
6. **Number of Replications:**
- The experiment was replicated twice

7. **Total Number of Experimental Runs:**
- 8 treatment combinations x 2 replications = 16 experimental runs per component

Component 1

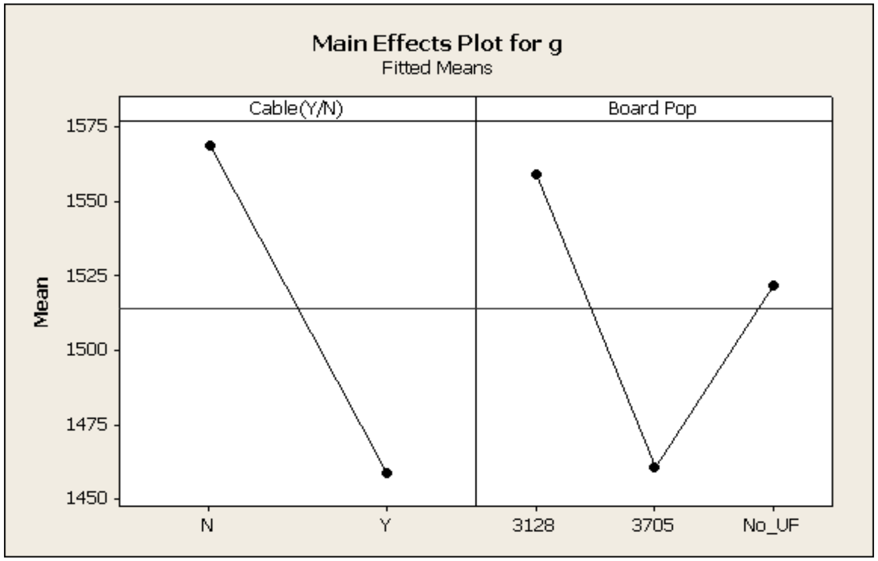


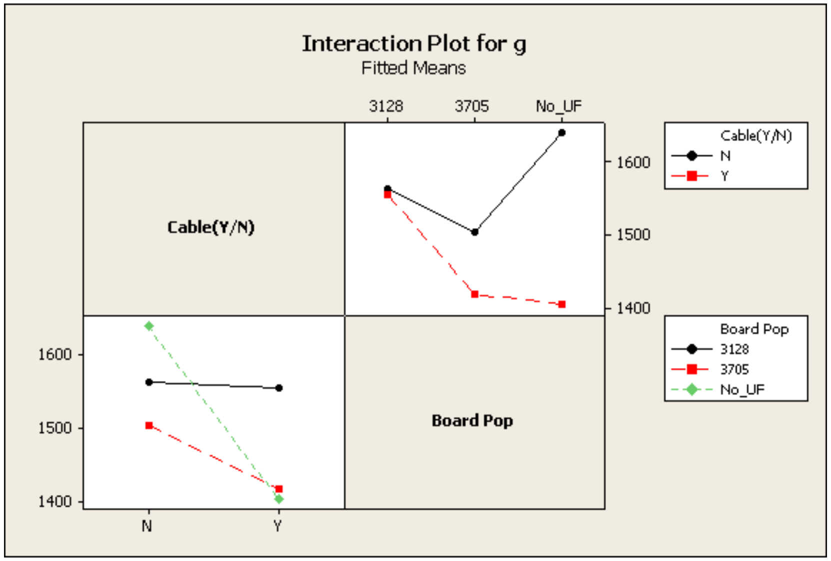


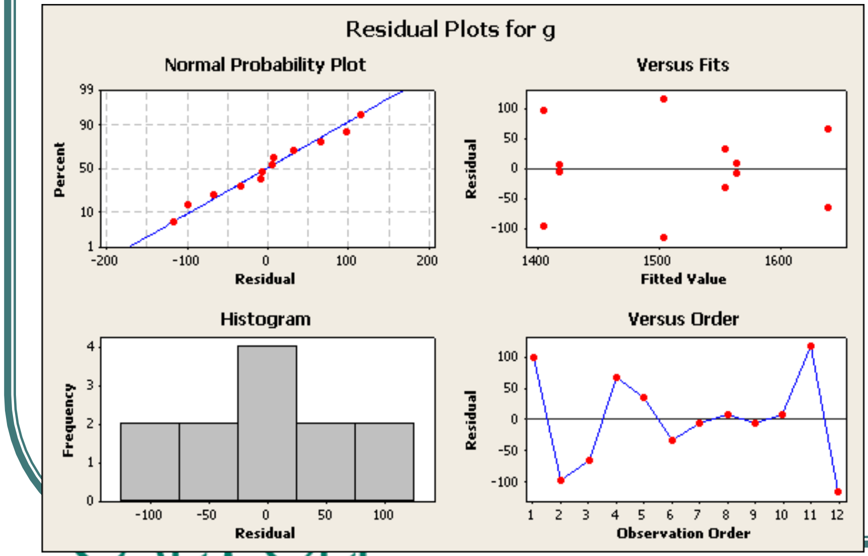


Source	P
Cable(Y/N)	0.208
Board Pop	0.789
Interactions	0.825

Component 2

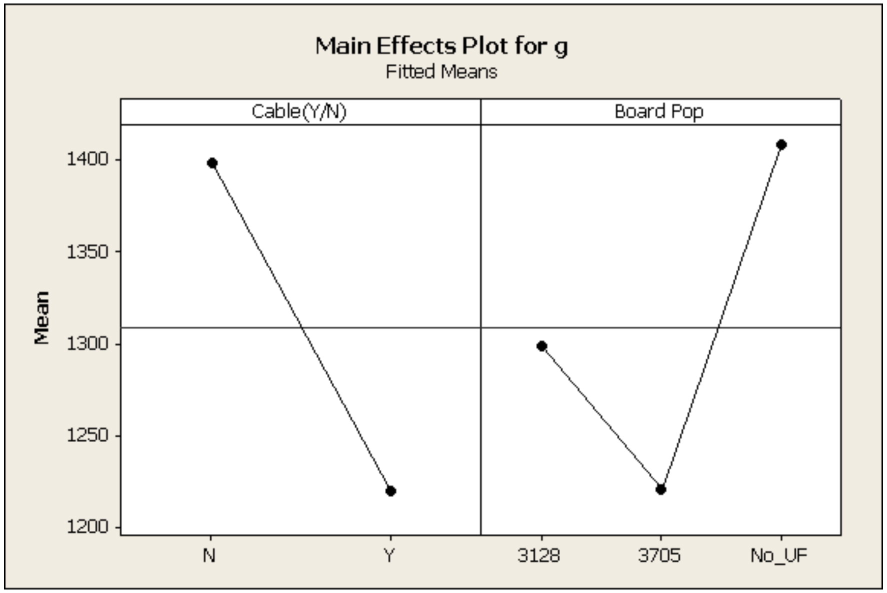


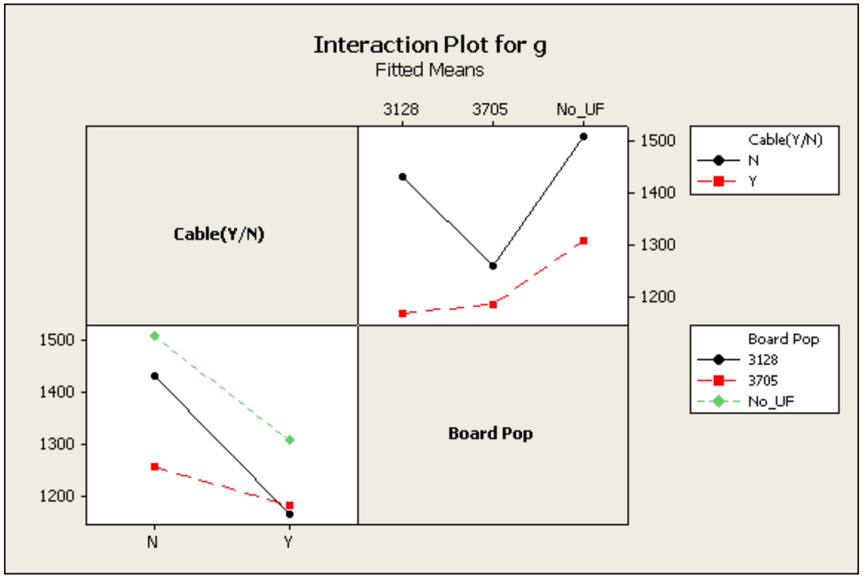


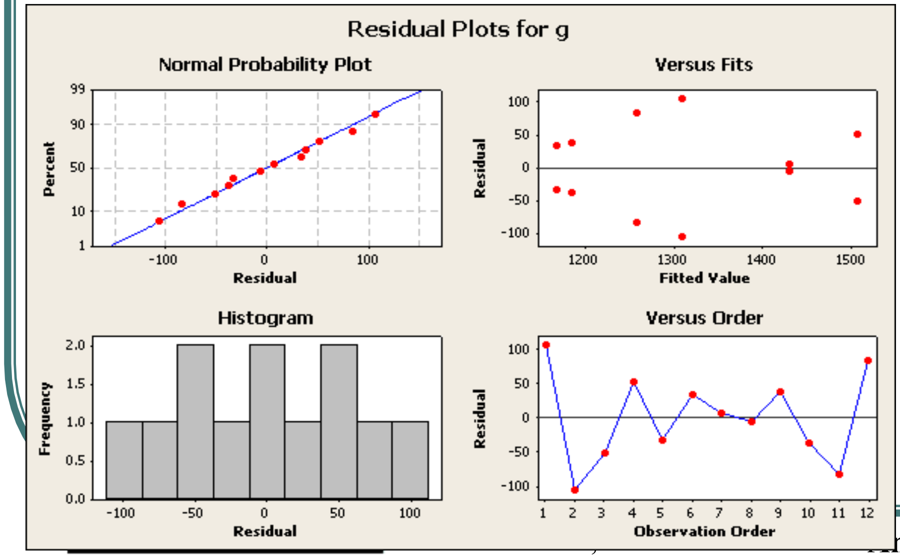


Source	P
Cable(Y/N)	0.101
Board Pop	0.418
Interactions	0.325

Component 3

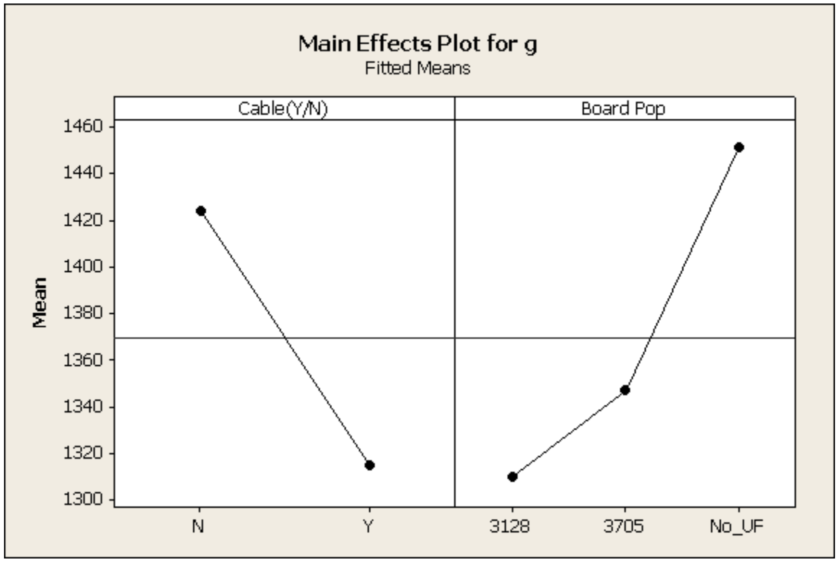


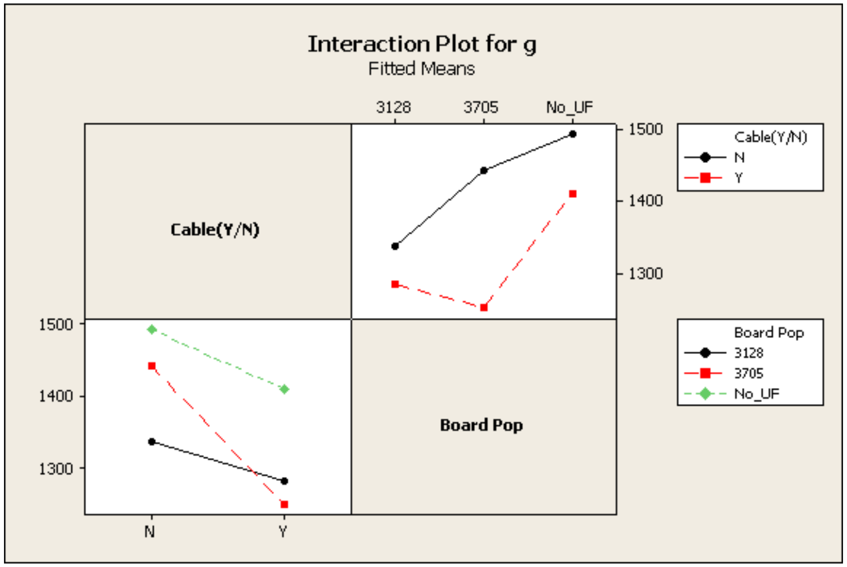


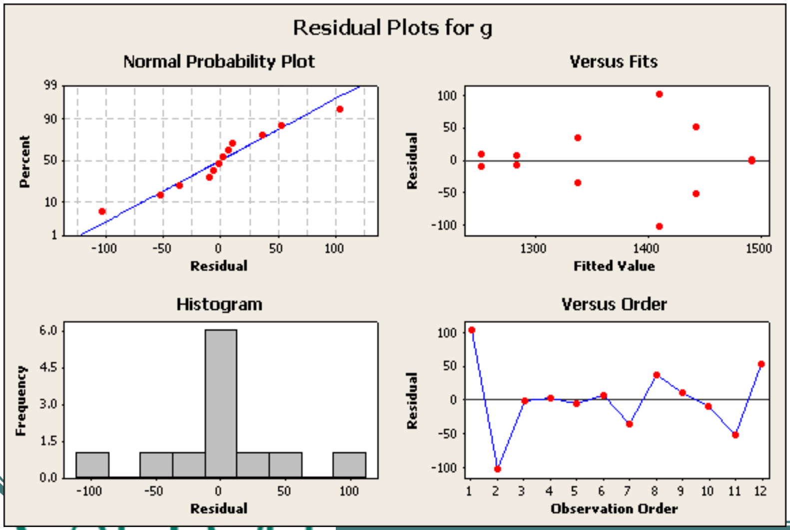


Source	P
Cable(Y/N)	0.013
Board Pop	0.065
Interactions	0.371

Component 4

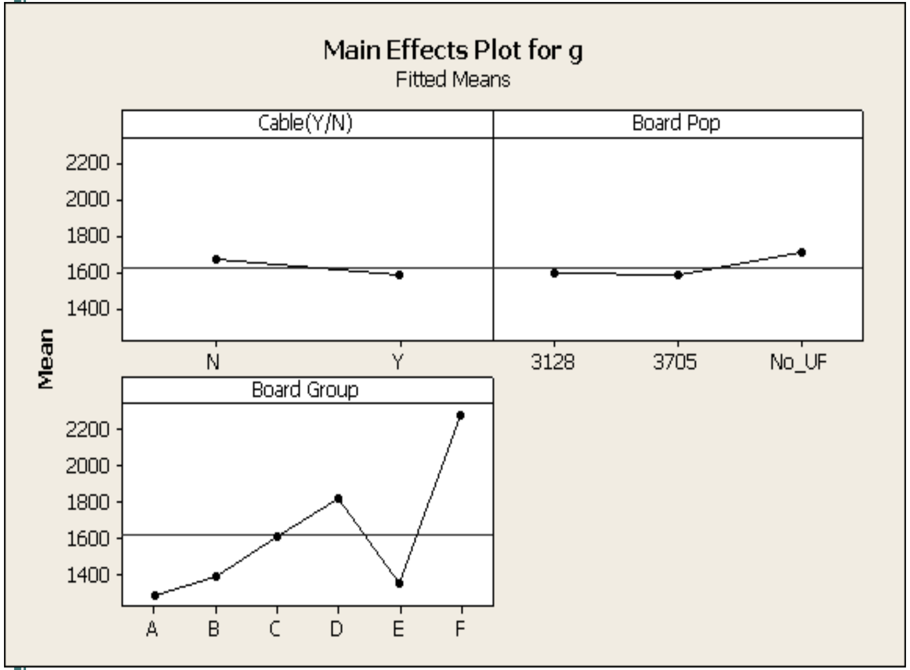


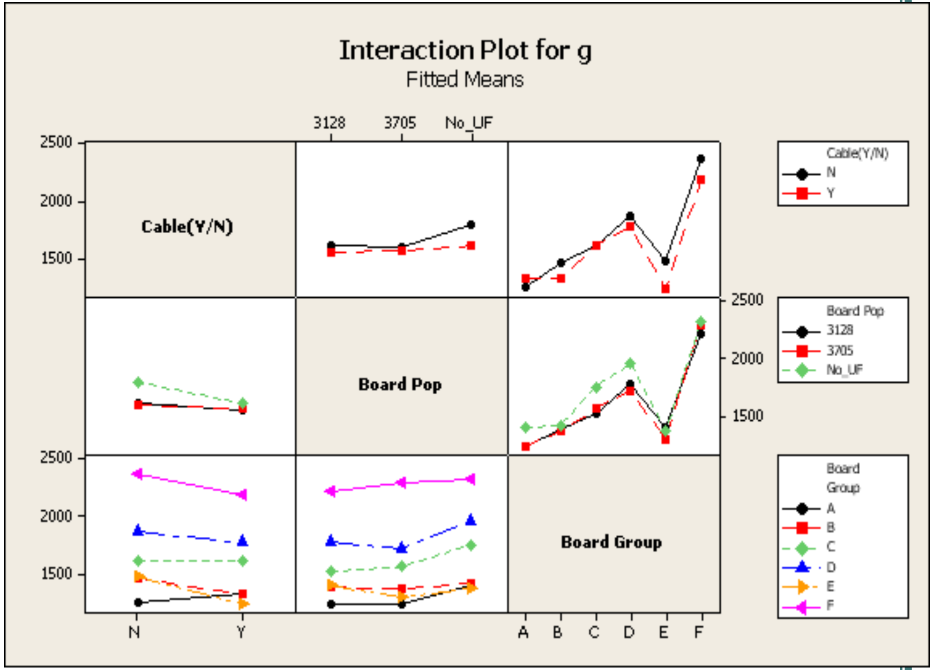


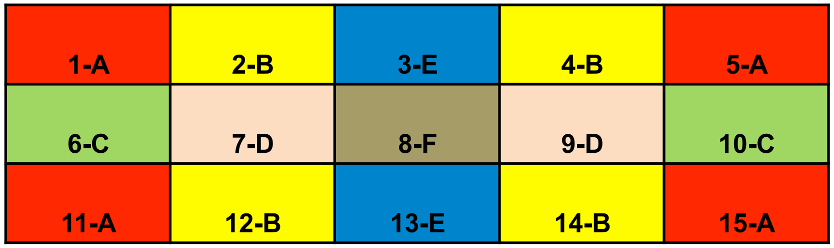


Source	P
Cable(Y/N)	0.037
Board Pop	0.069
Interactions	0.402

JEDEC Component Locations for Test Boards





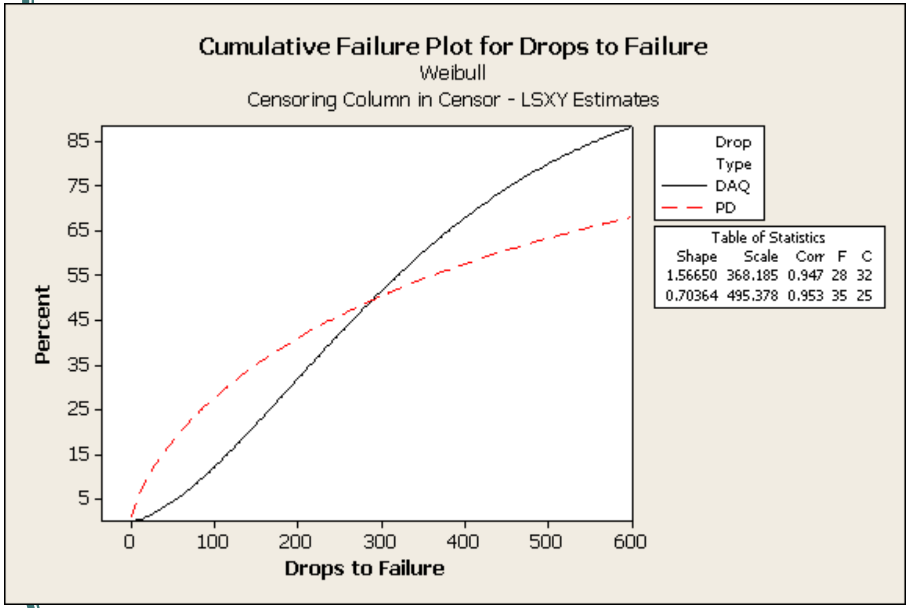


1-A	2-B	3-E	4-B	5-A
6-C	7-D	8-F	9-D	10-C
11-A	12-B	13-E	14-B	15-A

Source	P
Cable(Y/N)	0.005
Board Pop	0.003
Board Group	0.000
Cable(Y/N)*Board Pop	0.109
Cable(Y/N)*Board Group	0.010

Conclusions – Drop Test Method

- Data collection systems are different
  - At 1500g, differences are not significant
  - At 2900g, High-Speed DAQ consistently shows failures more quickly than post-drop



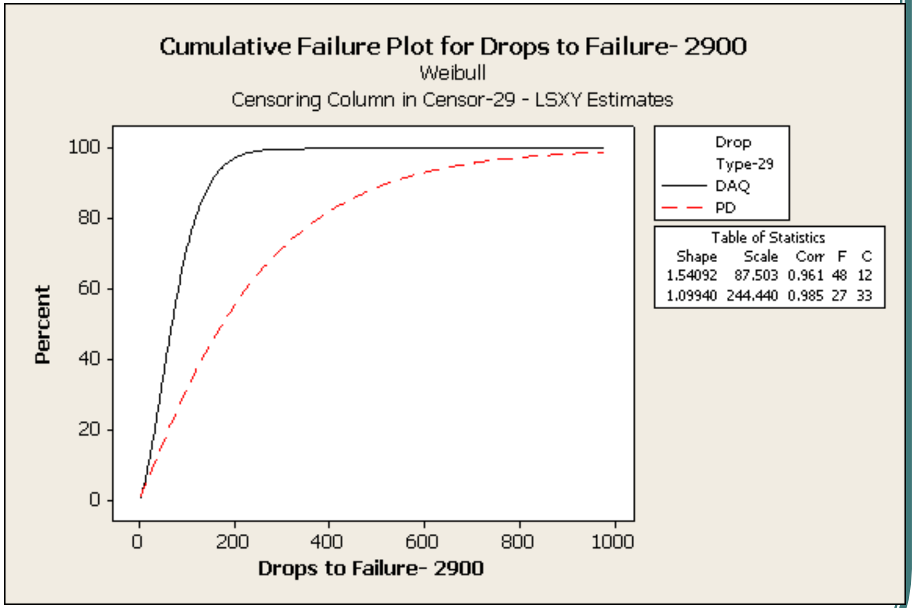
Cumulative Failure Plot for Drops to Failure

Weibull

Censoring Column in Censor - LSXY Estimates

Table of Statistics

Shape	Scale	Corr	F	C
1.56650	368.185	0.947	28	32
0.70364	495.378	0.953	35	25



Cumulative Failure Plot for Drops to Failure- 2900

Weibull

Censoring Column in Censor-29 - LSXY Estimates

Table of Statistics

Shape	Scale	Corr	F	C
1.54092	87.503	0.961	48	12
1.09940	244.440	0.985	27	33