Drop Test Reliability of Lead-free Chip Scale Packages

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Agenda

- Introduction
- Test Vehicle
- Failure Detection Systems
- Reliability Data
- Failure Analysis
- Local Acceleration on Component Location
- Conclusions

Prior Work

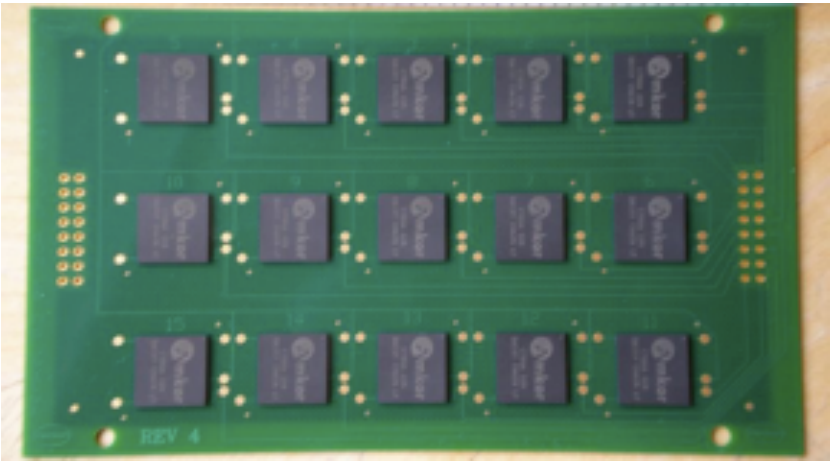
- Lead-free SnAgCu solders with various alloy additives (Syed 2006, Pandher 2007) and low-silver content (Lai 2005, Kim 2007) have been studied to improve drop impact reliability of solder joints
- Underfills (Zhang 2003, Toleno 2007) and corner bonding (Tian 2005) have been used to improve drop impact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

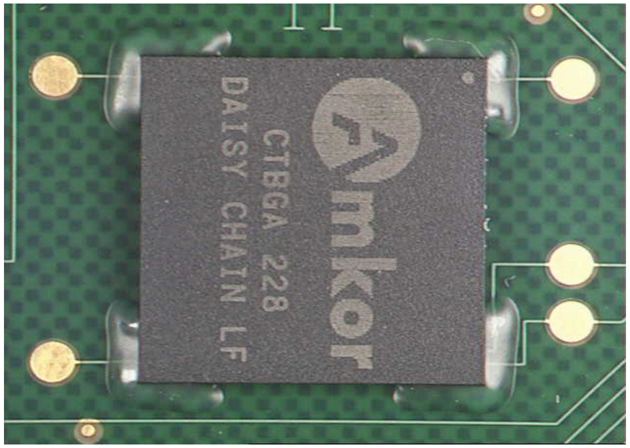
Test Vehicle

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

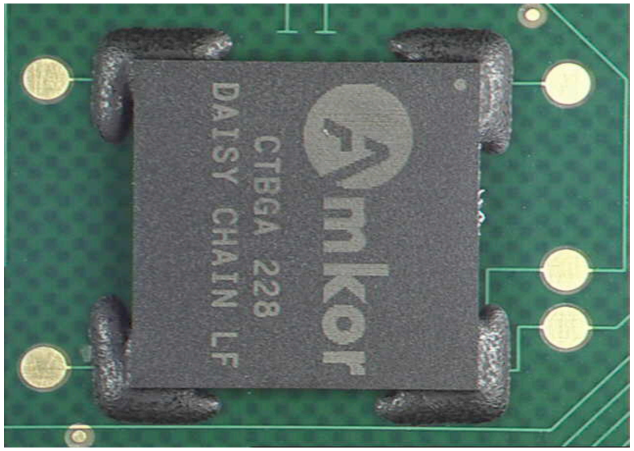


Edge Bond Materials

- 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



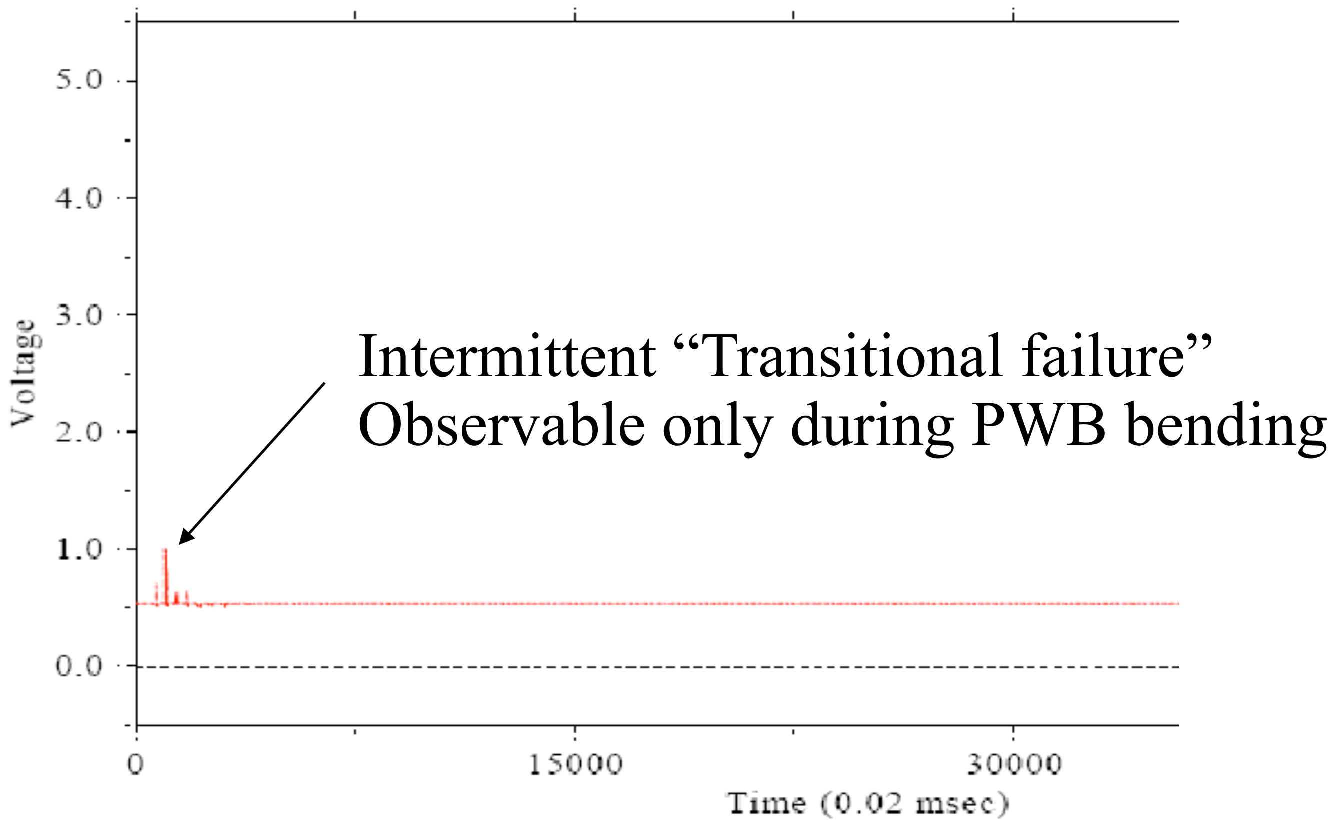
Epoxy

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



Failure Event

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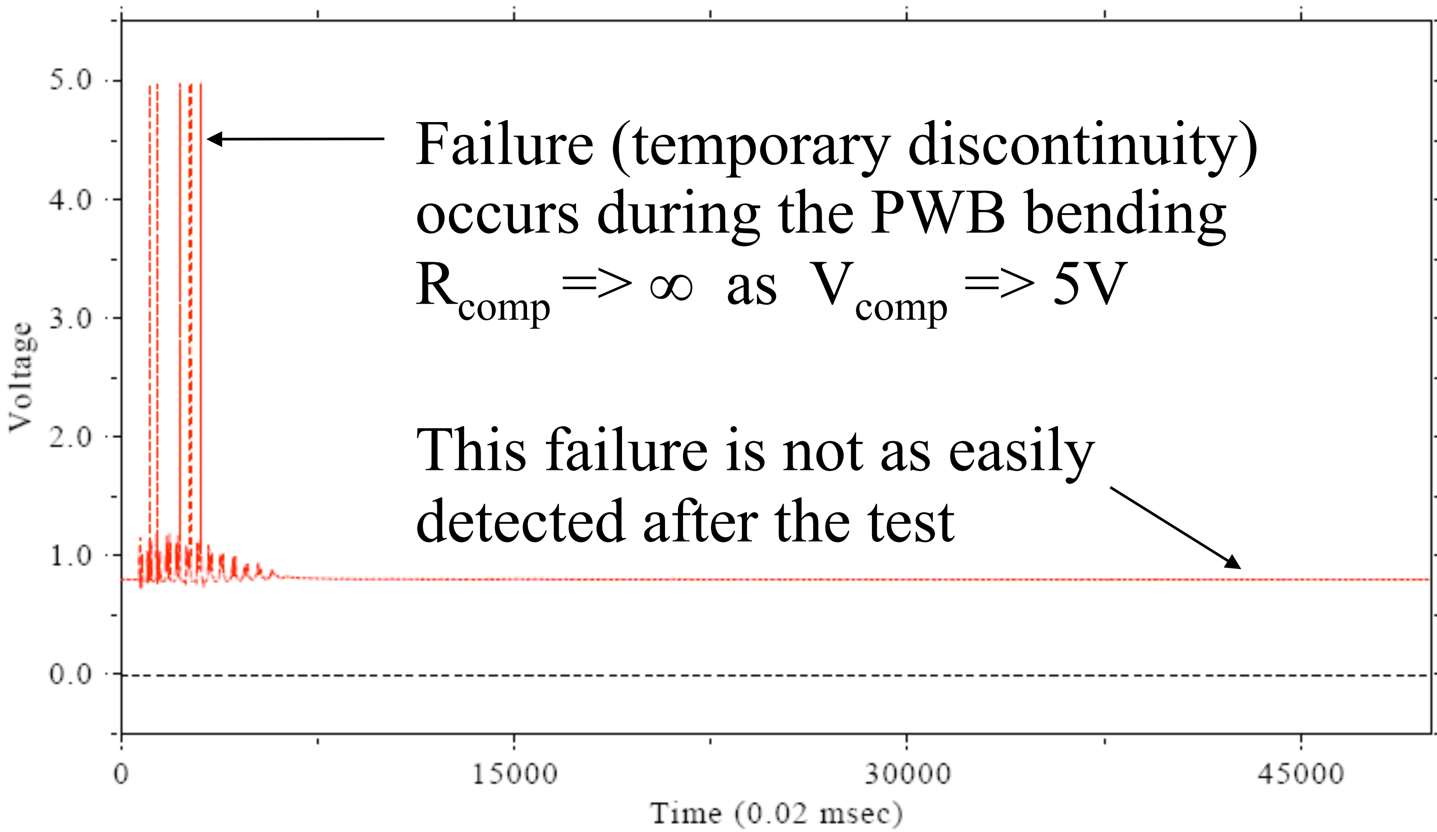

Failure Event

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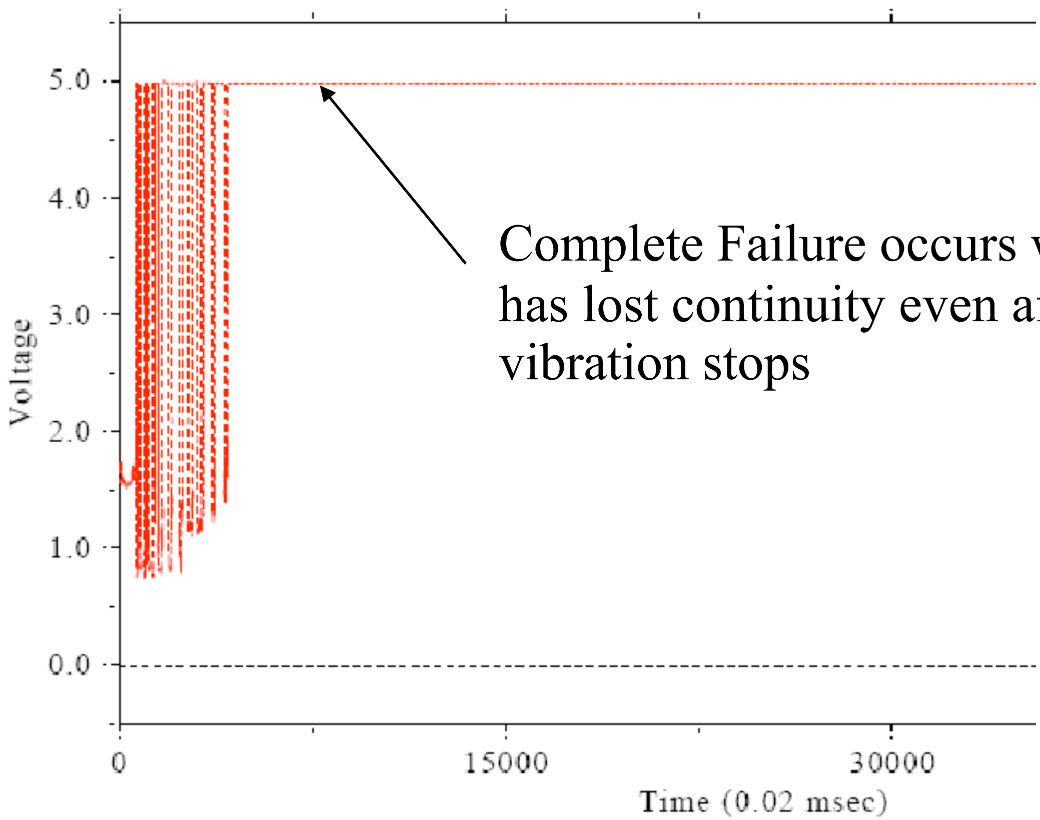
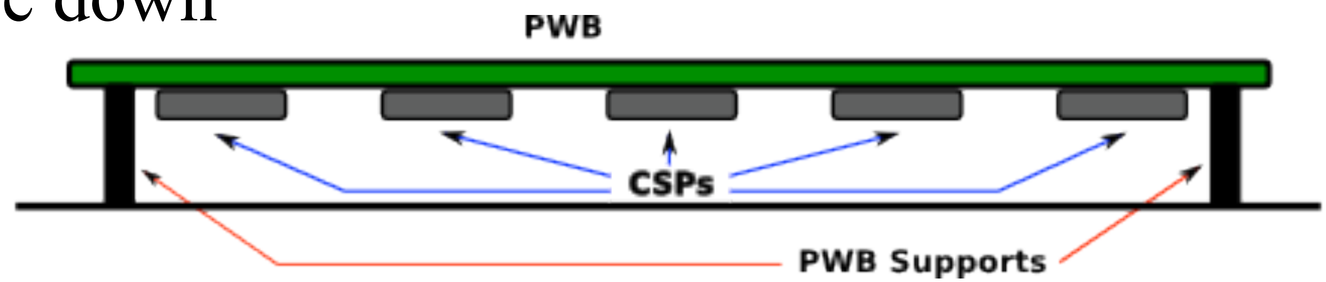


Complete Failure occurs when the daisy-chain has lost continuity even after the PWB vibration stops

Test Vehicle Drop Orientation

- Test vehicle is always mounted with components face down



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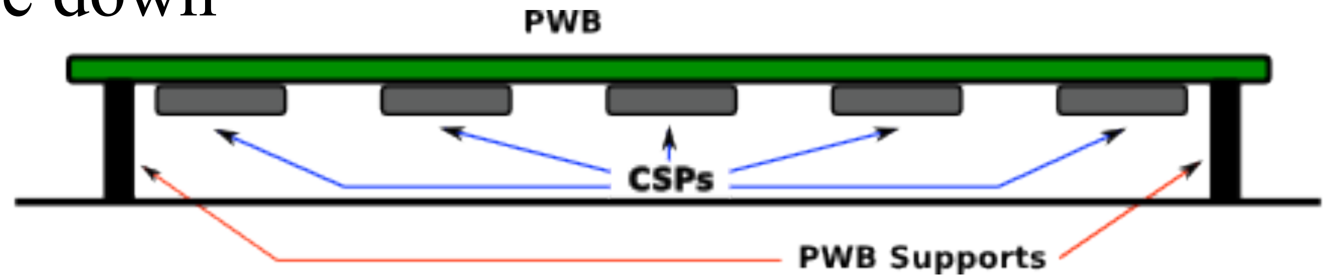

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- <u>Reliability Data</u>
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Reliability Test Design

- 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

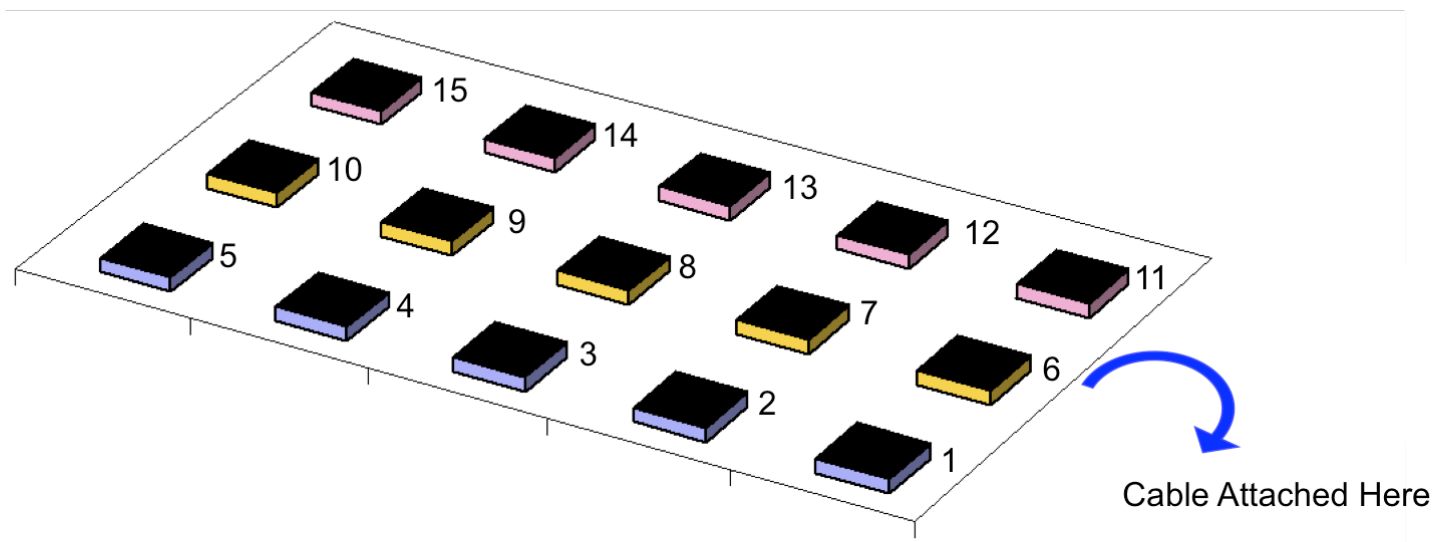

Table 2 - DAQ No Edge-bond

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**				

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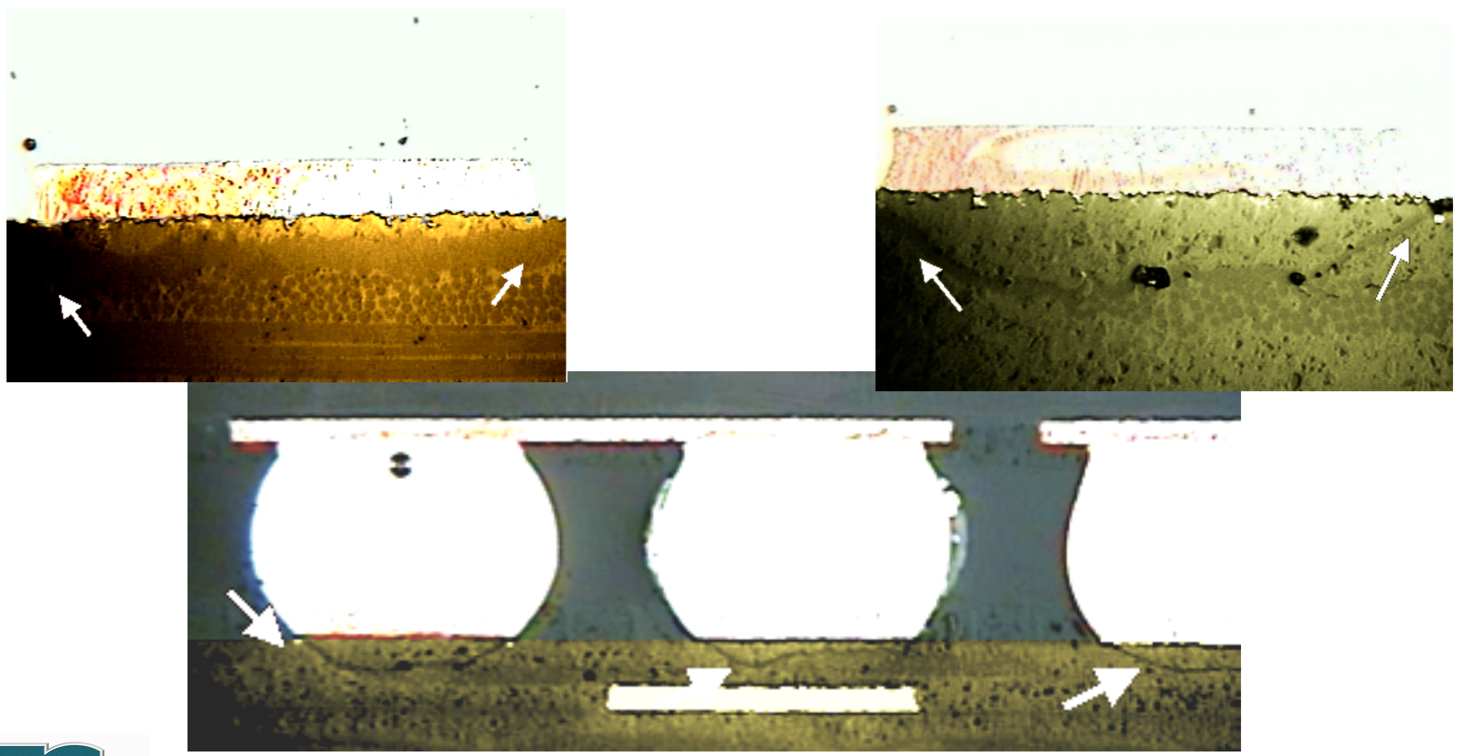
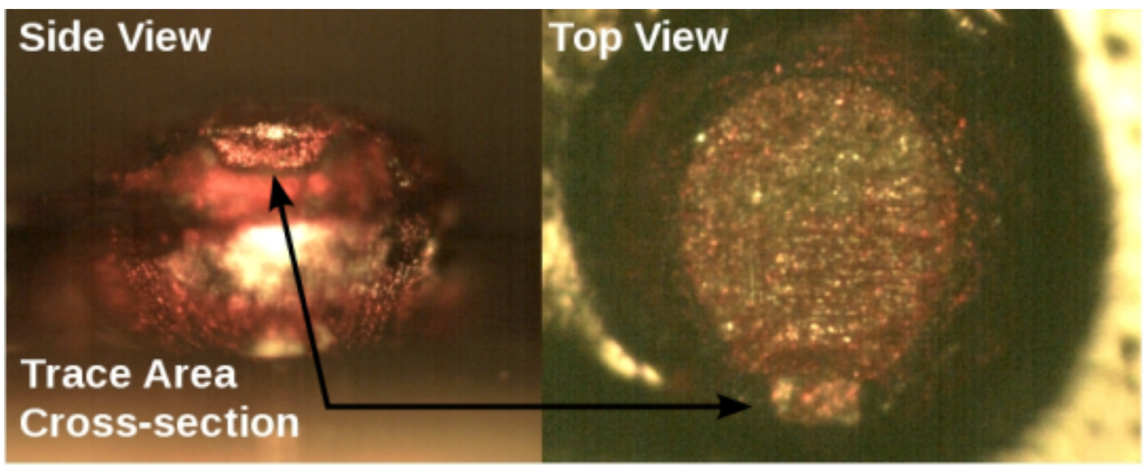
Cracking Under Pads (Cratering)

Cracks develop underneath the copper pads, allowing the copper pad to lift away from the board

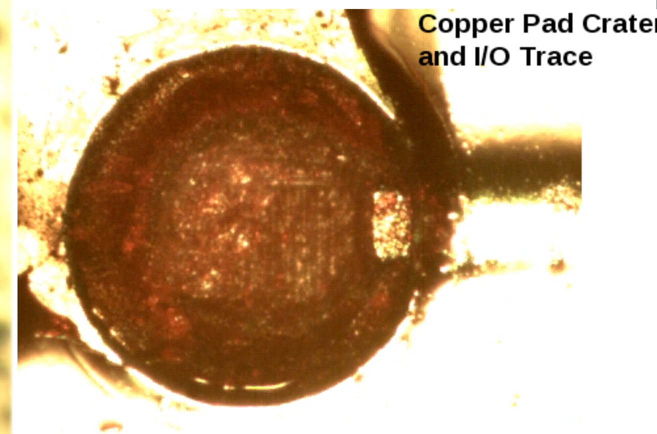


I/O Trace Failure

- Input/Output (I/O) traces that connect to the daisy-chain ‘resistor’ were often broken
- Many components had this broken trace and no other identifiable failure



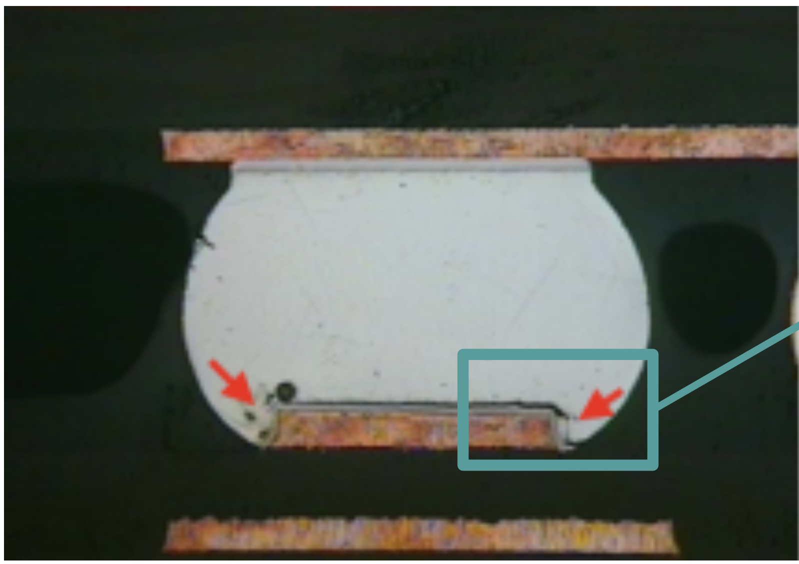
Component side

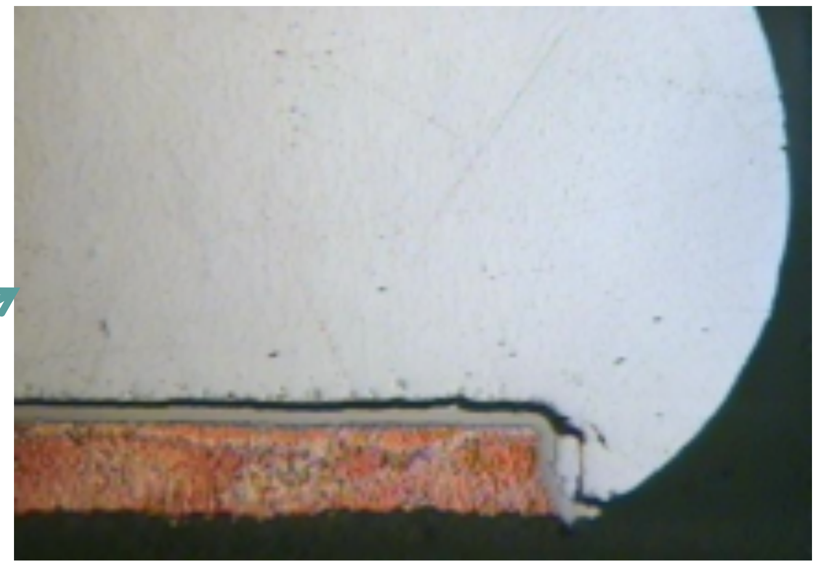


Board side

Solder Fracture Failure

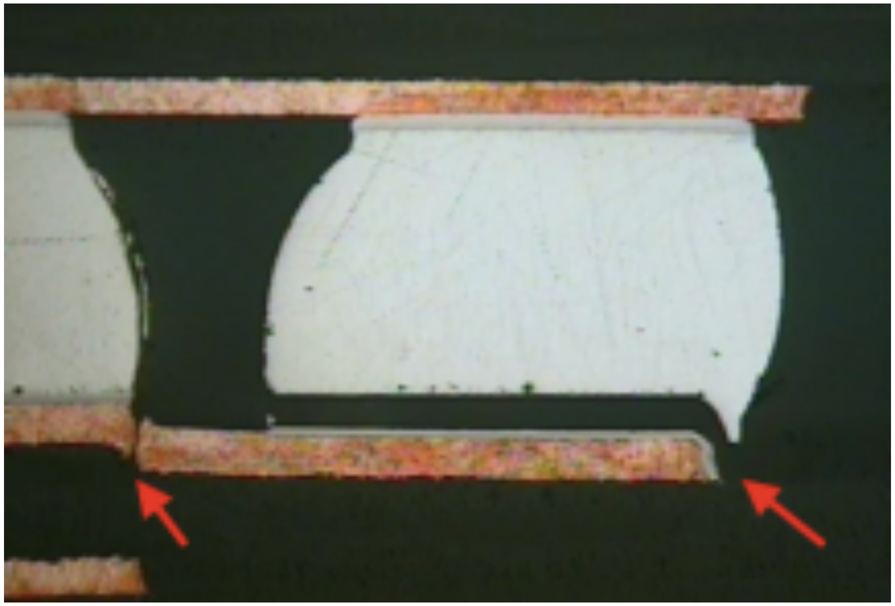
- Cross-sectioned solder joint is shown to be cracked near the board side copper pad





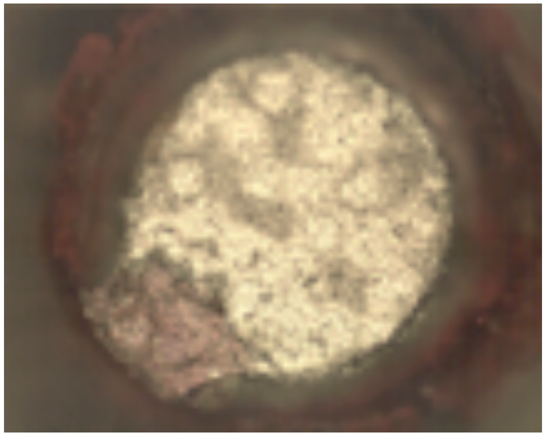
Solder Fracture Failure

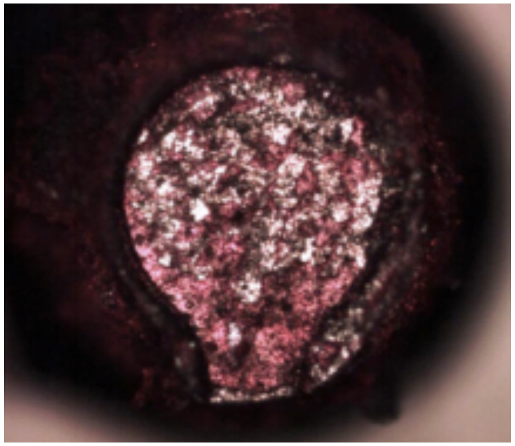
- Cross-sectioned solder joint is shown to be cracked near the board side copper pad
- Copper trace failure also shown (left side)



Dye Stained Solder Fractures

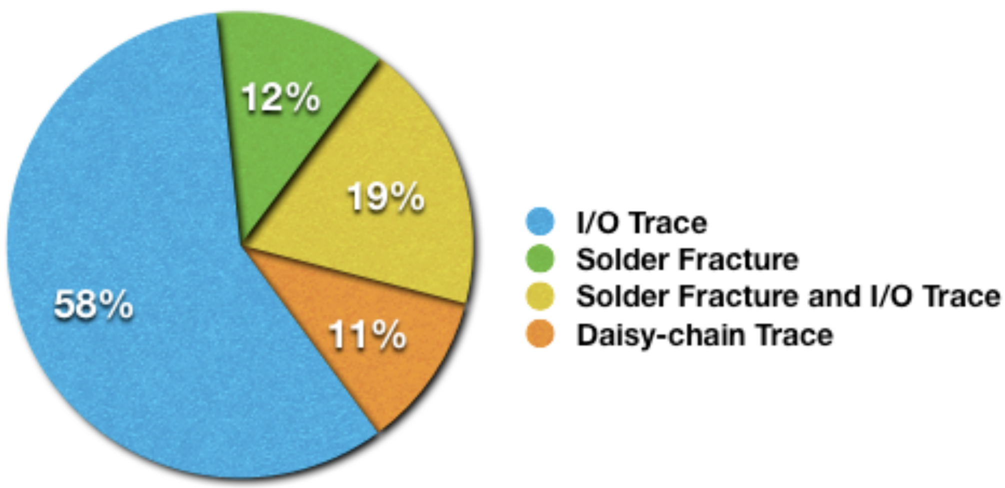
- Dye stained solder fractures were found
  - Partial solder fracture (left) was not completely fractured before the component was removed
  - Complete solder fracture (right) was fully fractured before the component was removed



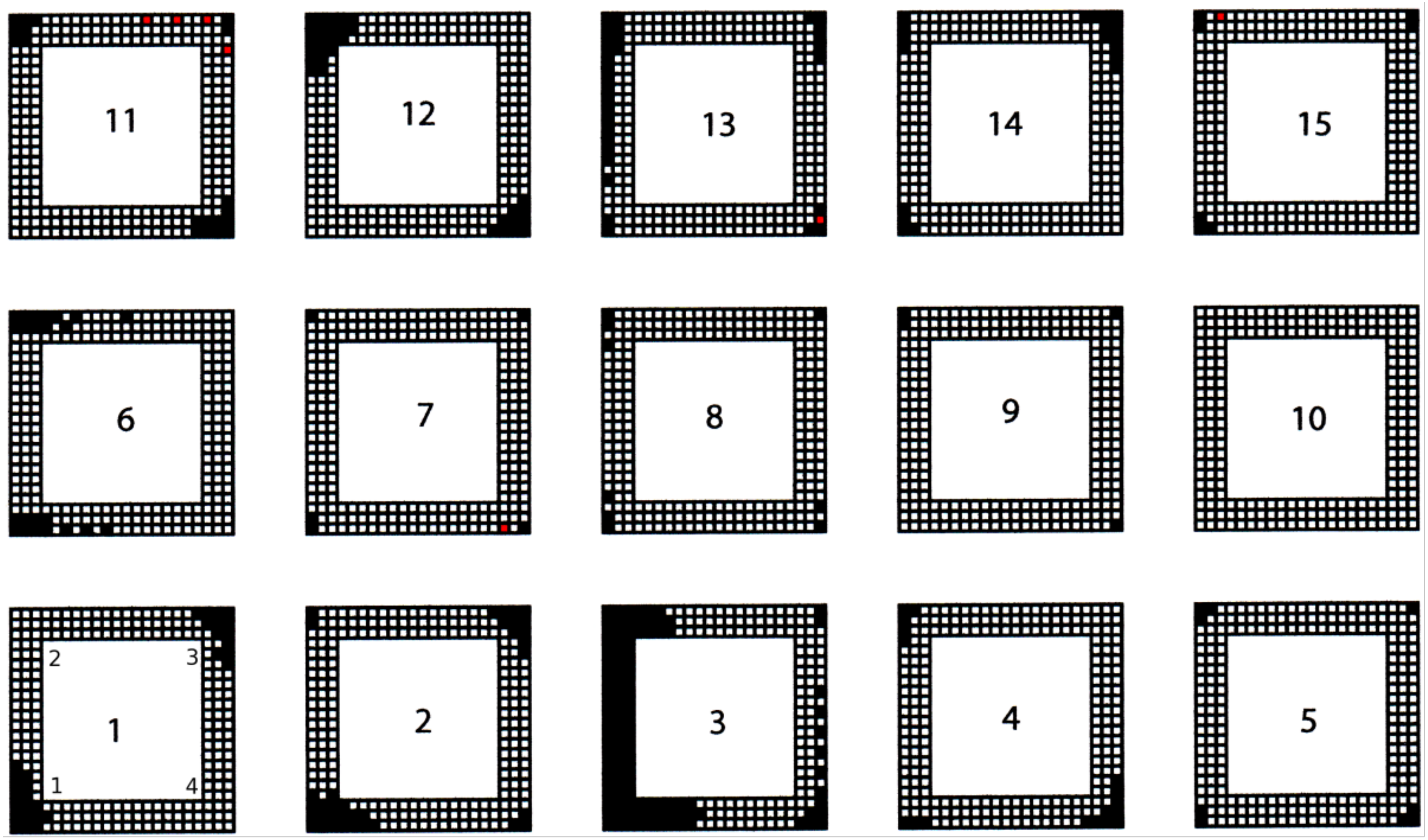


Failure Mode Comparison

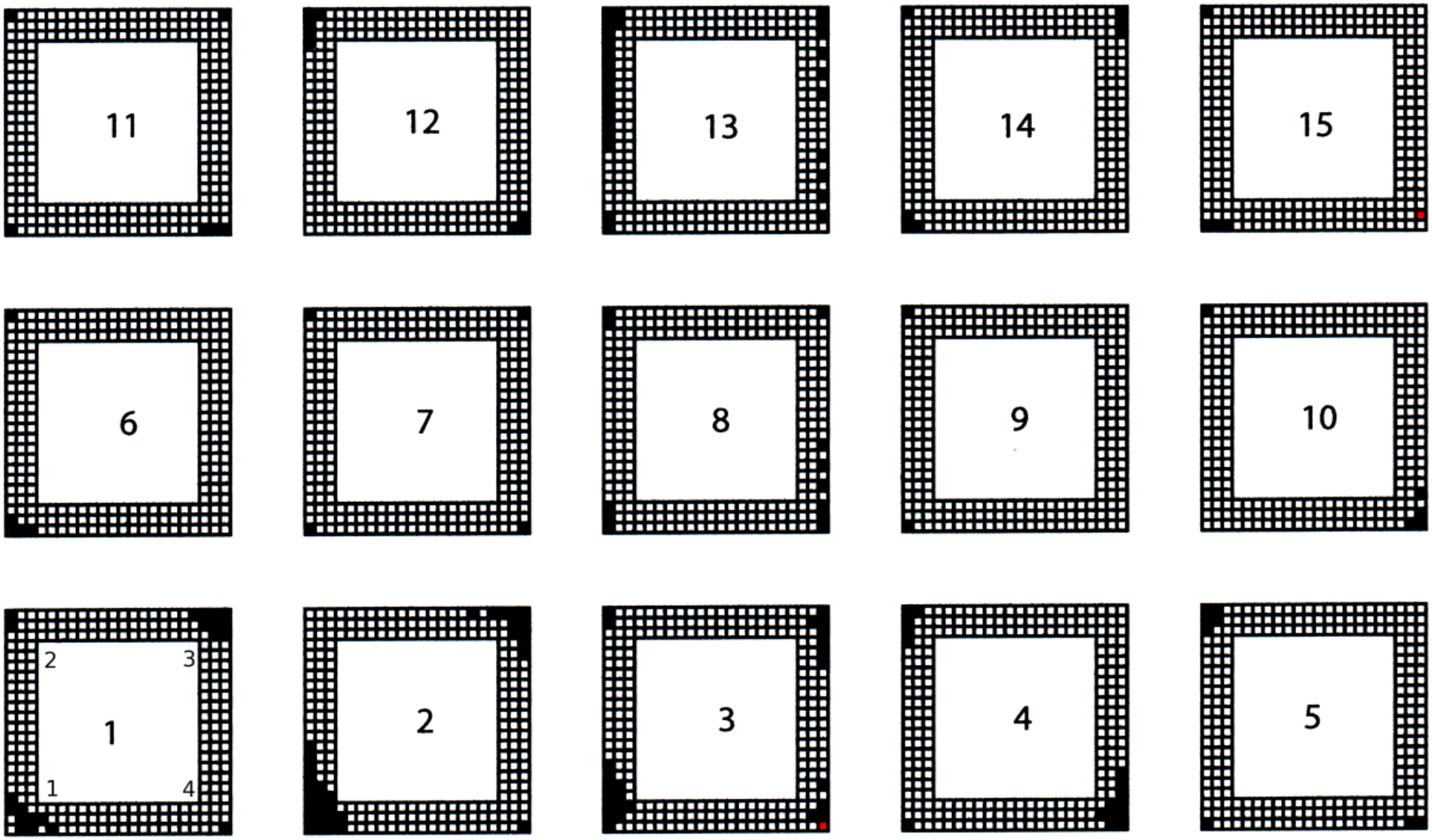
- I/O Trace and Daisy-chain Trace failures are both caused by pad cratering
- Pad cratering was present on 88% of electrically failed components, and is directly responsible for 69% of all electrical failures



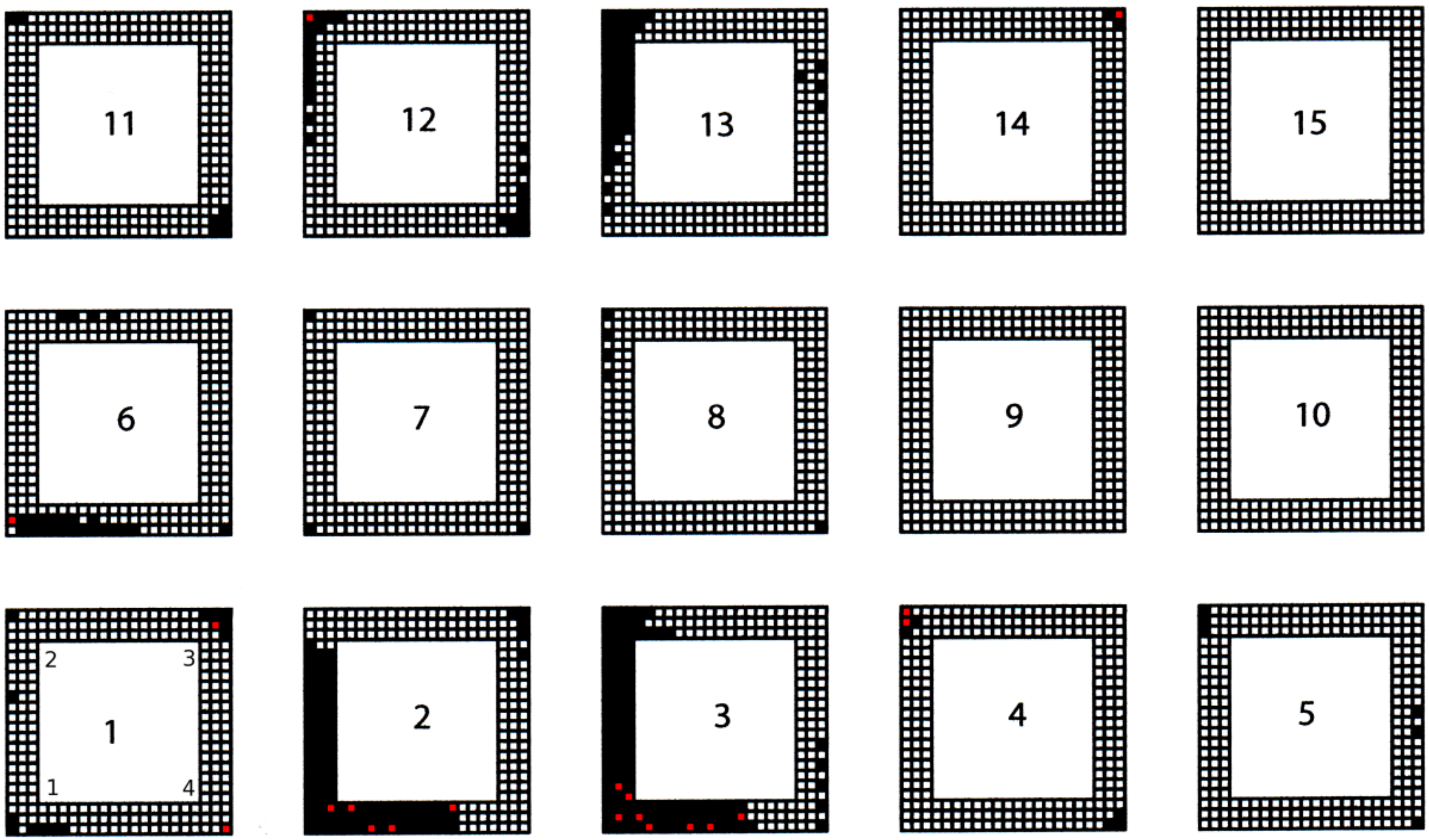
Failures After 10 Drops (No EB)



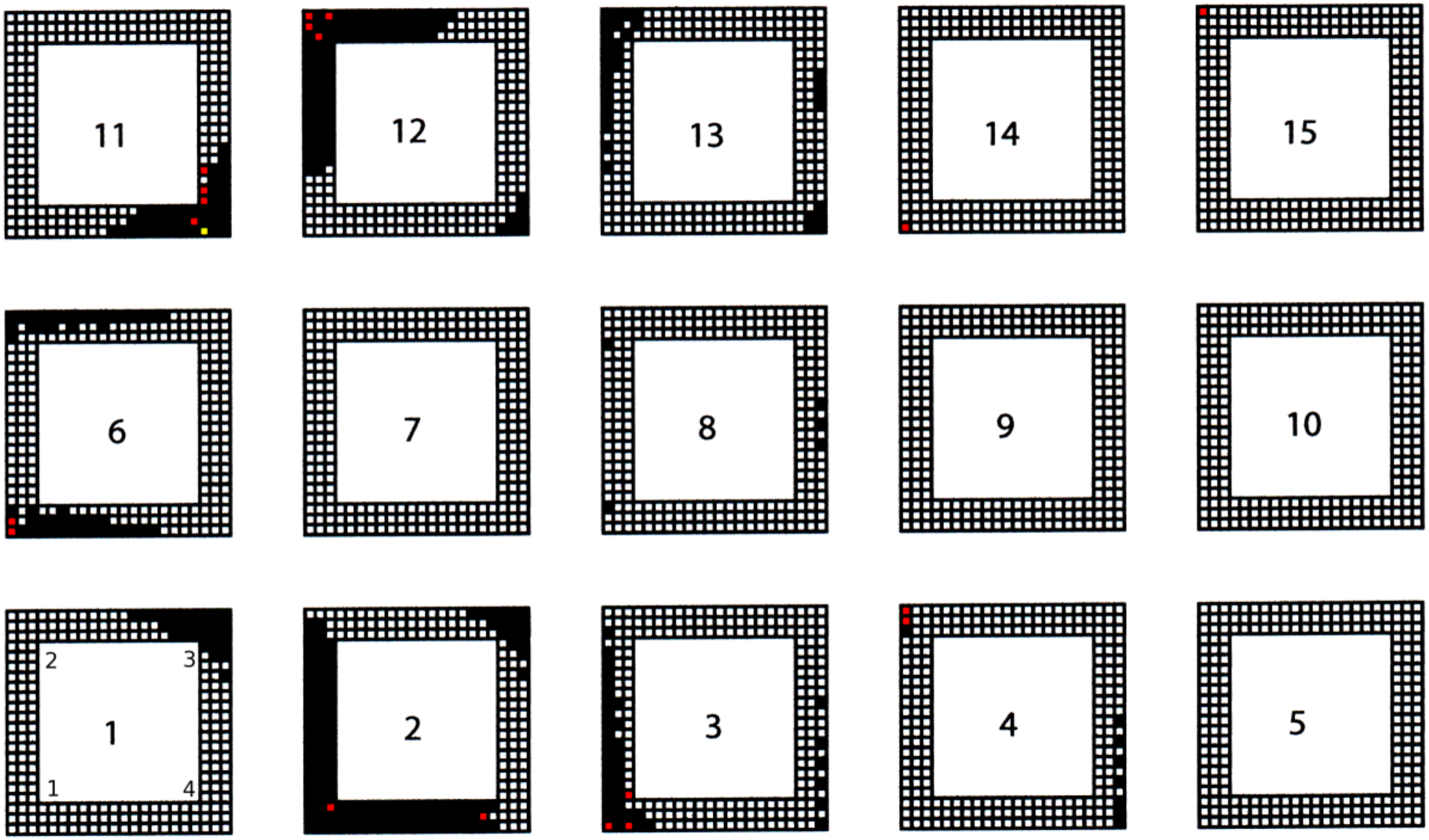
Failures After 14 Drops (No EB)



Failures After 325 Drops (Epoxy EB)



Failures After 279 Drops (Acrylic EB)



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

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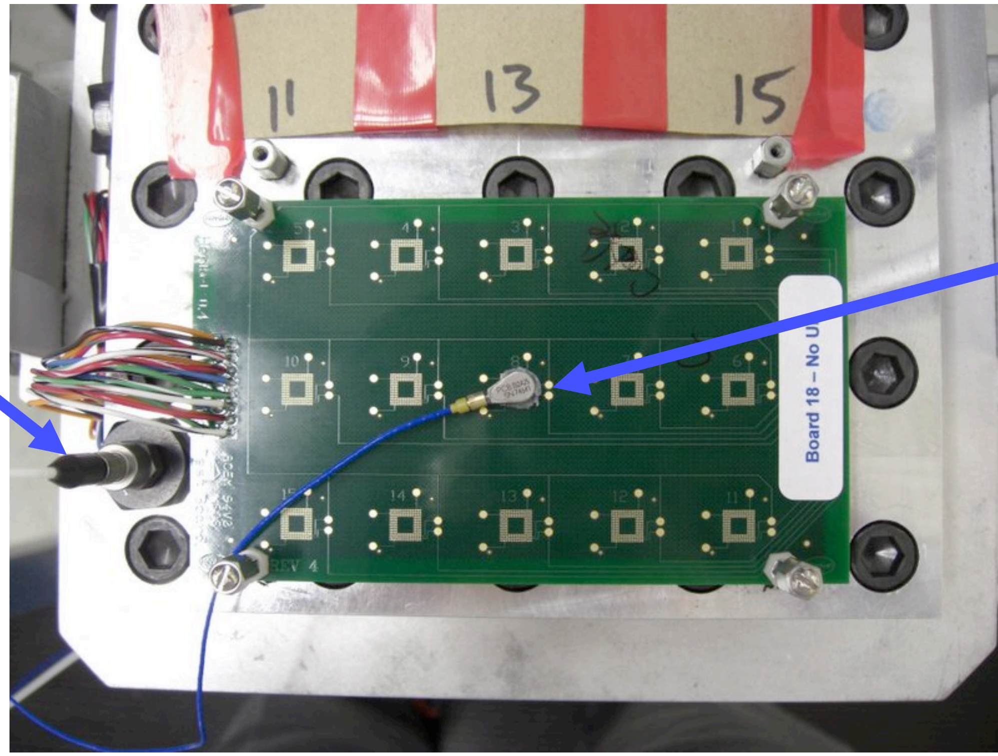
Local Acceleration Conditions

Accelerometer on Drop Table

Accelerometer above Component C8



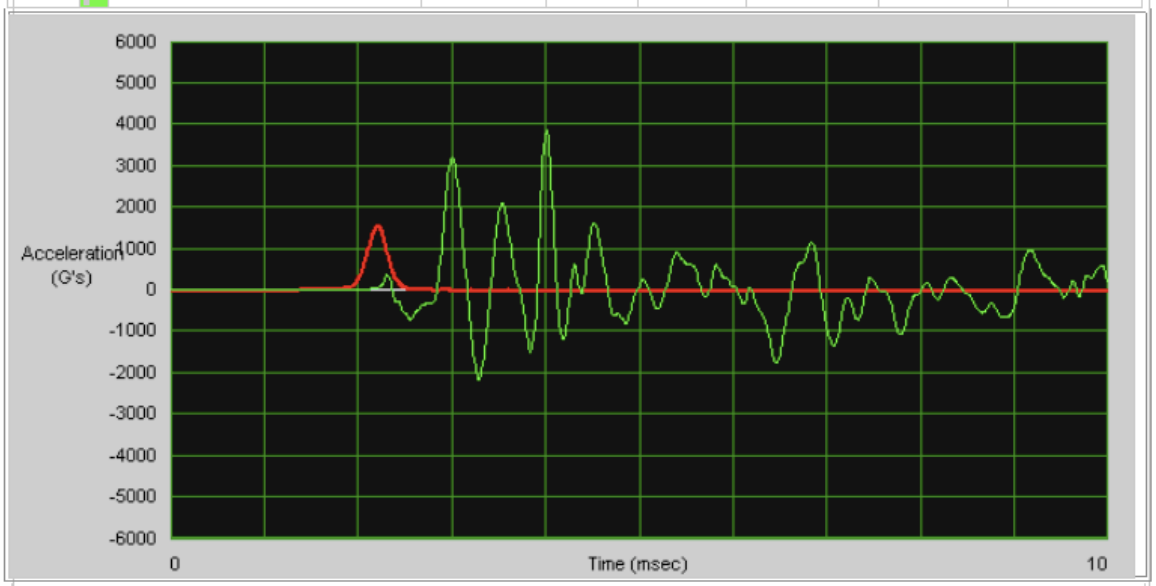
Testing the acceleration condition on the board and table simultaneously

Local Acceleration Conditions

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

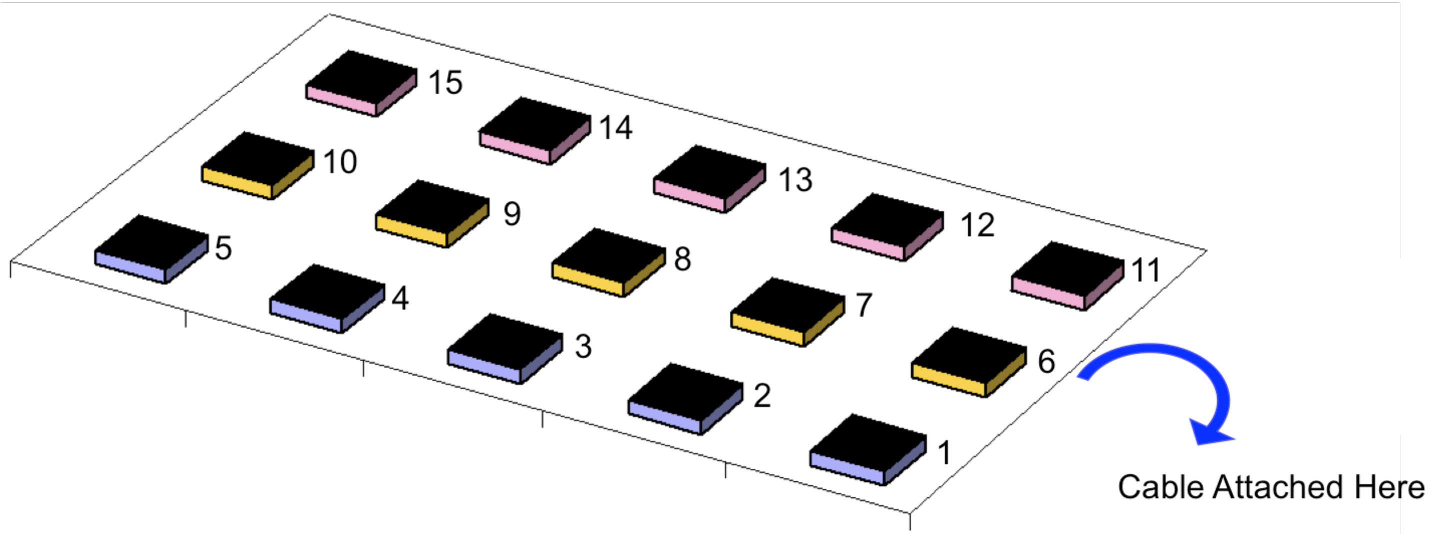
Acceleration vs Time

		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

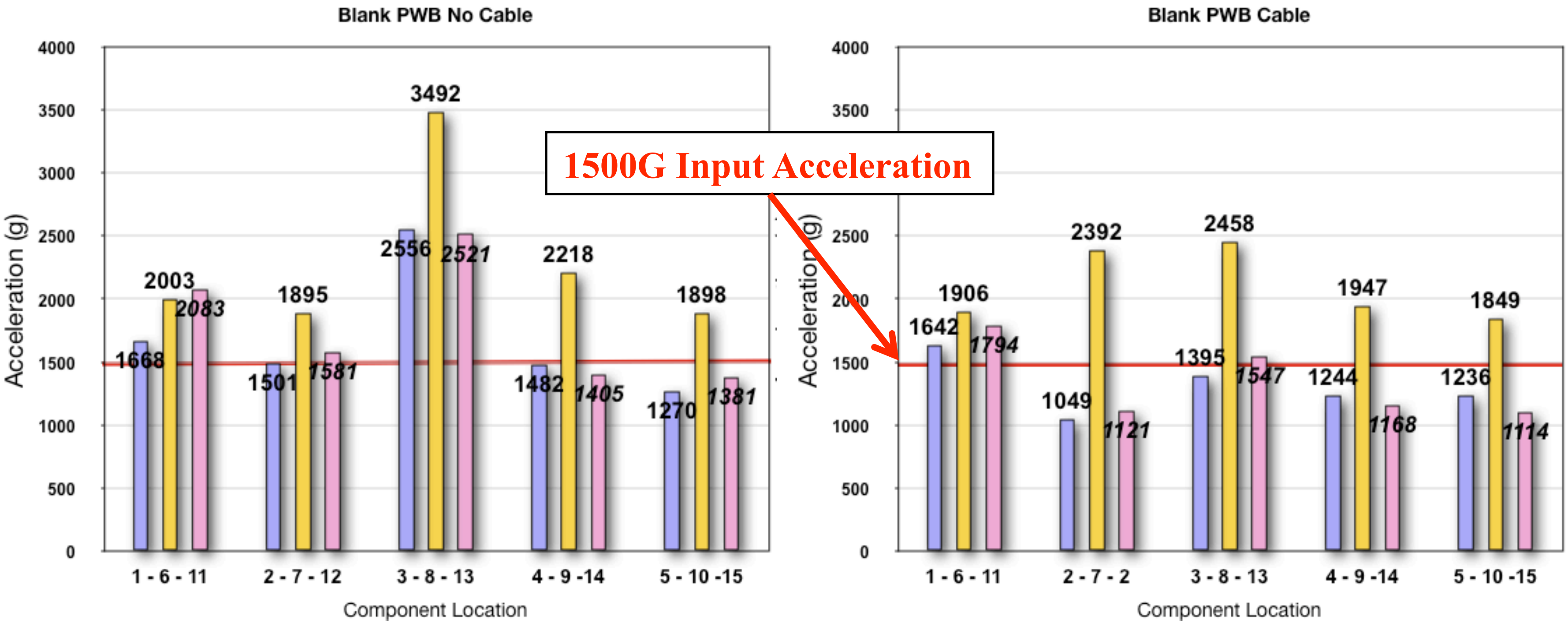


Component Locations

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

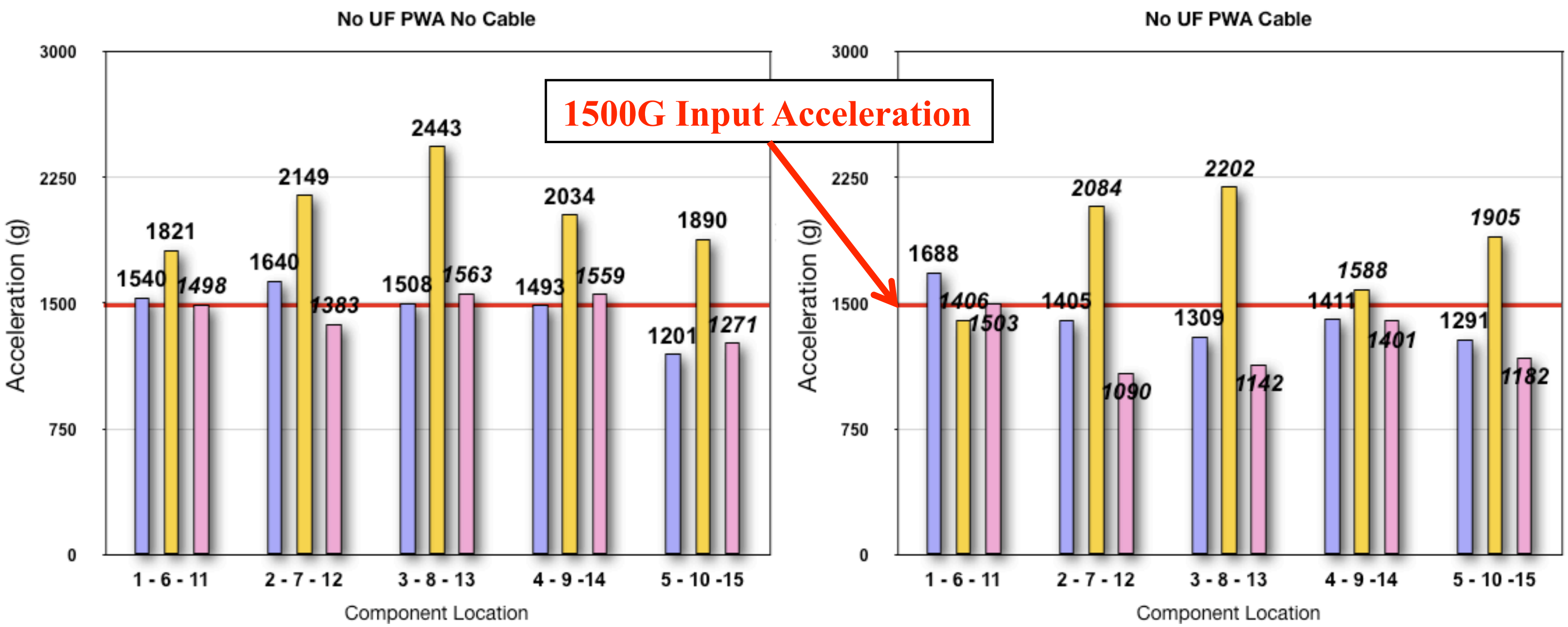


Blank PWB – No Cable vs Cable



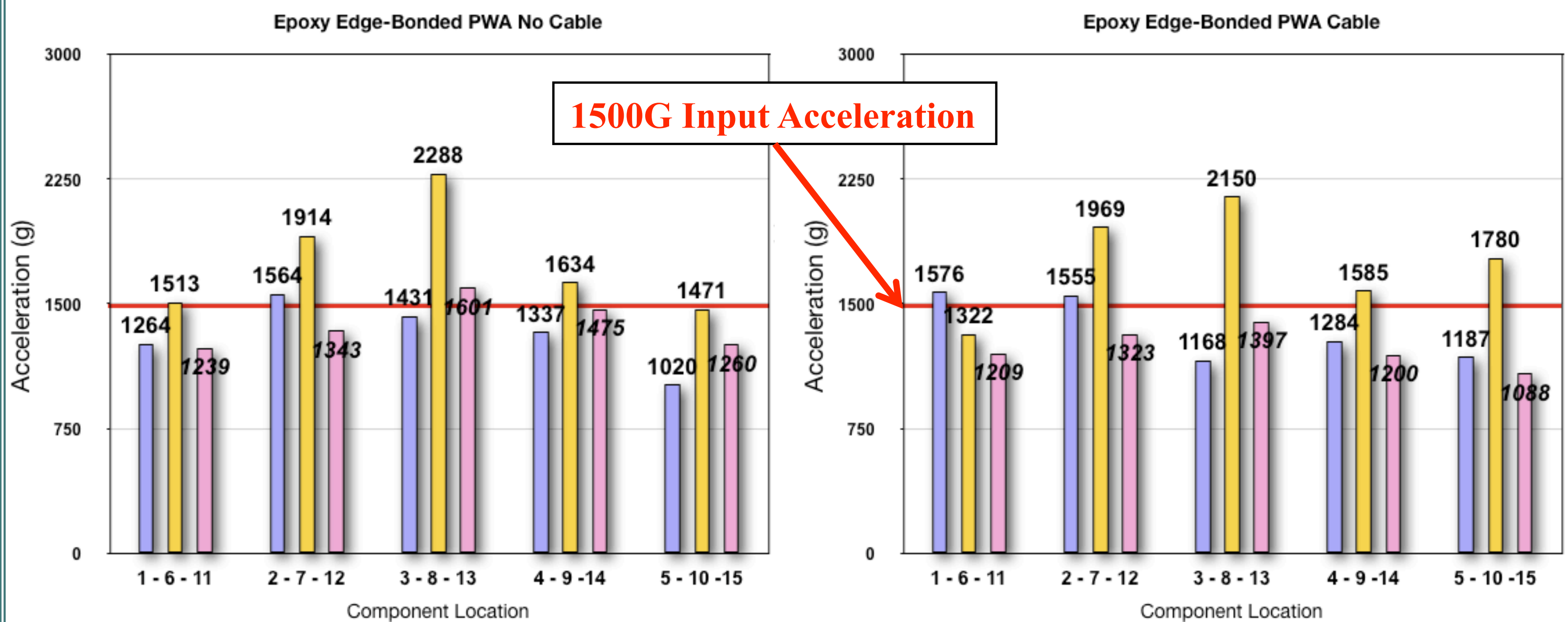
- Symmetry of acceleration peaks has shifted (C7 vs C9)
- Maximums greatly reduced by cable (C3, C13, C8)

Populated PWB – No Edge Bond



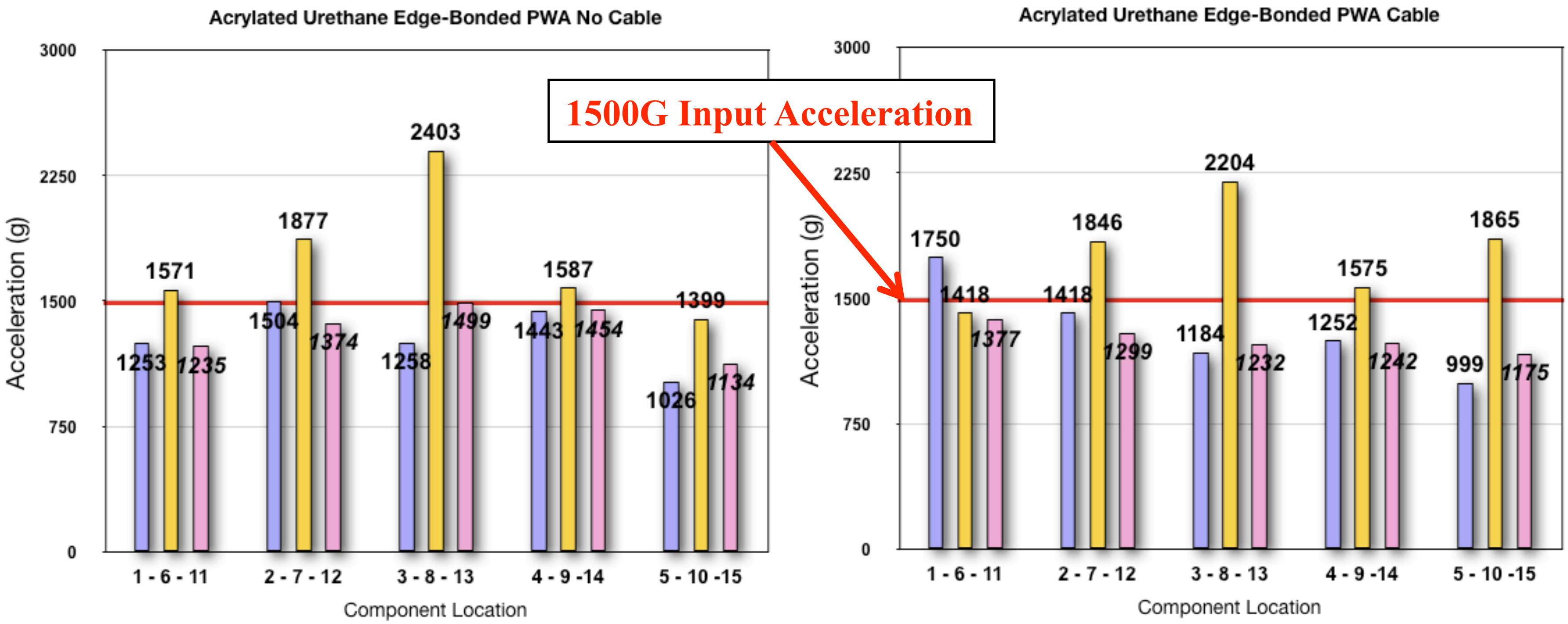
- Dampening due to the cable seems less significant than with blank PWB (both graphs are more similar)

Epoxy Edge Bonded CSPs



- 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

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

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

Acknowledgements

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- Office of Naval Research (ONR)

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- Society of Manufacturing Engineers Education Foundation
- Surface Mount Technology Association San Jose Chapter

Supplemental Slides

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.)

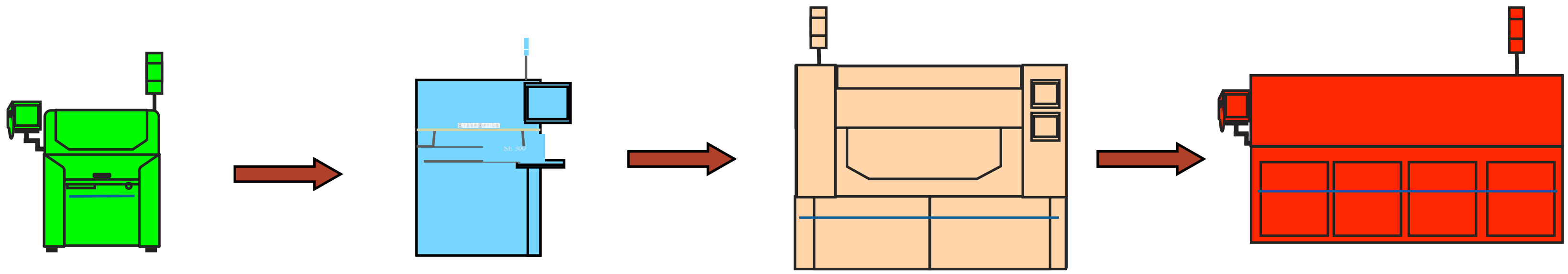
- Mobile electronic devices also…
  - Are complicated and expensive
  - Are easily damaged by drop impacts
  - Are designed to be lightweight and portable
- Drop test reliability is:
  - The study of how well a device or part survives repeated drop impacts
  - A process to determine where design improvements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

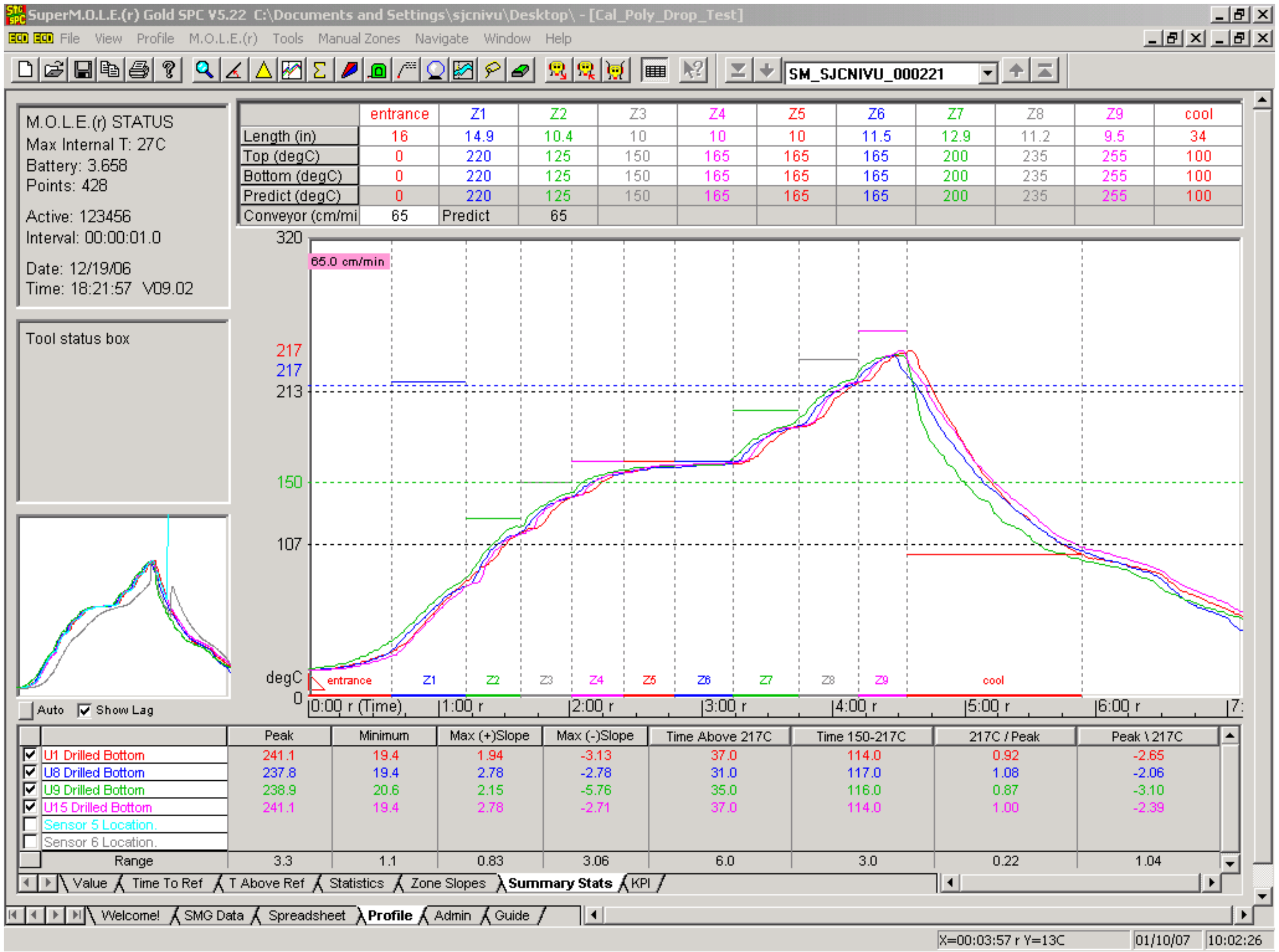
Siemens F5 Placement

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

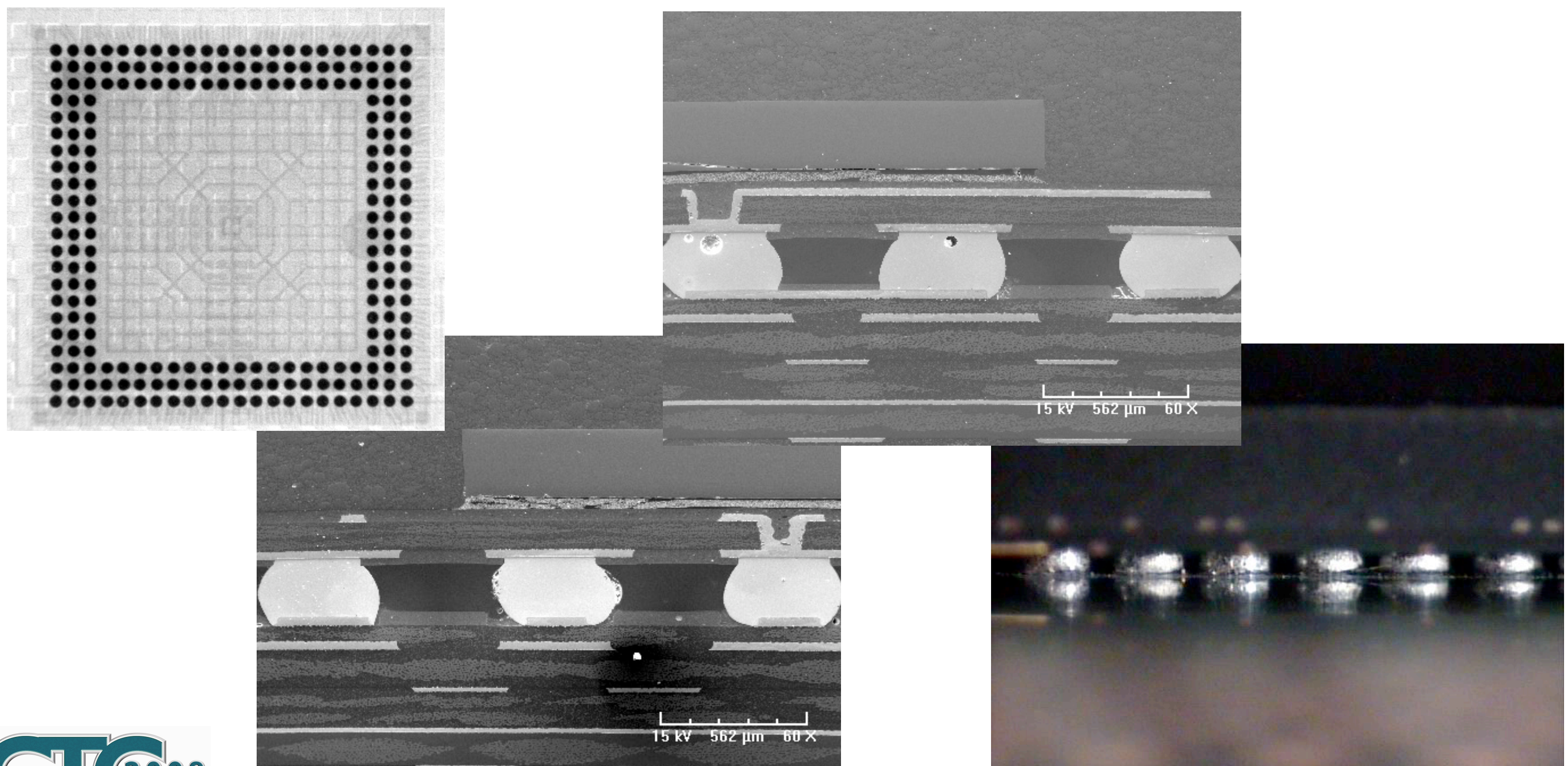


	entrance	Z1	Z2	Z3	Z4	Z5	Z6	Z7	Z8	Z9	cool
Length (in)	16	14.9	10.4	10	10	10	11.5	12.9	11.2	9.5	34
Top (degC)	0	220	125	150	165	165	165	200	235	255	100
Bottom (degC)	0	220	125	150	165	165	165	200	235	255	100
Predict (degC)	0	220	125	150	165	165	165	200	235	255	100
Conveyor (cm/mi	65	Predict	65								

	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

Solder Joint Integrity after Assembly

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

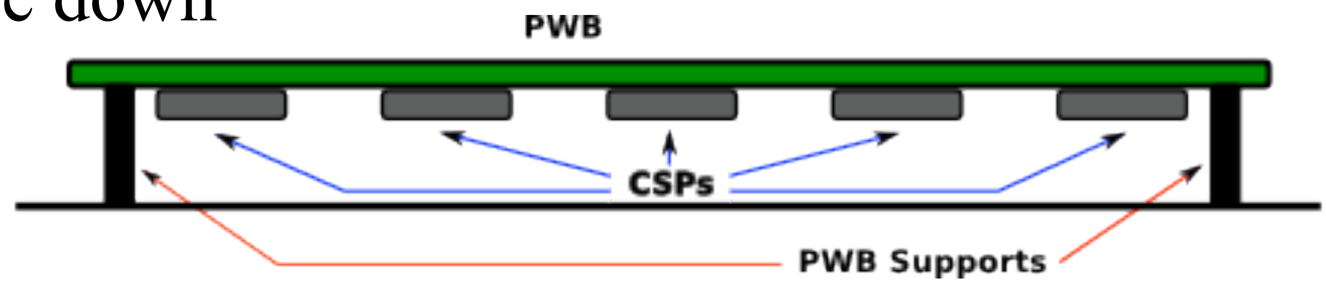


Definition: Drop Impact Failure

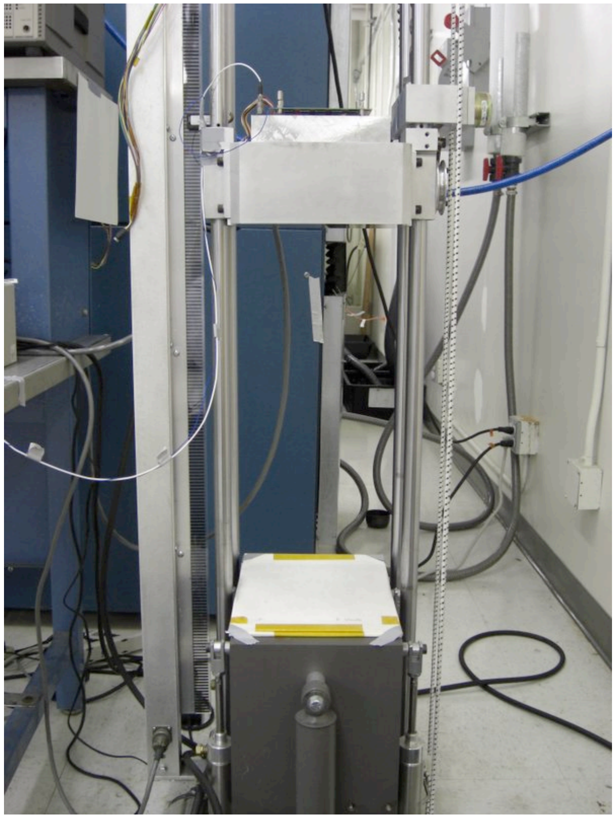
- Drop impact failure…
  - Occurs when the electrical connections in the device are damaged so that it no longer functions as designed
  - Is typically detected by change of resistance or loss of continuity in board level circuits
  - May be either a permanent or intermittent condition

Test Vehicle Drop Orientation

- Test vehicle is always mounted with components face down

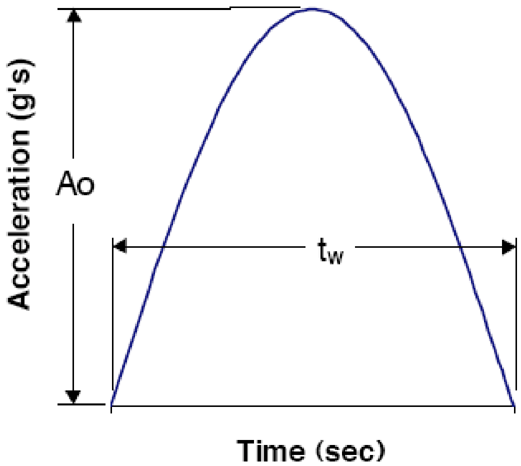


Drop Impact Input Acceleration



Lansmont MTS II Shock Tester

Typical Half-sine Acceleration Pulse



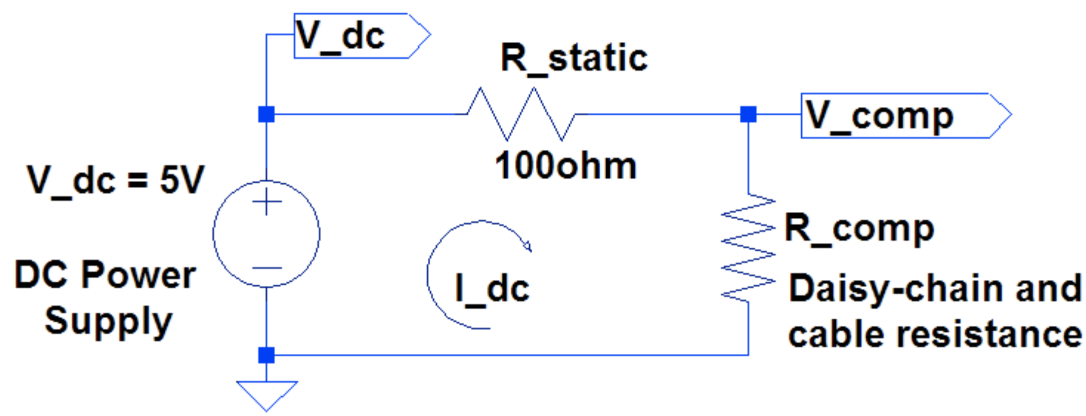
e.g. 1500g - 0.5ms
or 2900g - 0.3ms

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

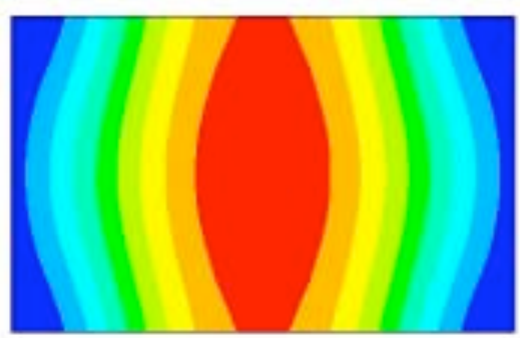
- Uses a single resistance measurement per drop, taken after the board vibration ceases
- The failure criteria is a 10 ohm static rise from nominal daisy-chain resistance

Post-Drop Resistance Measurement

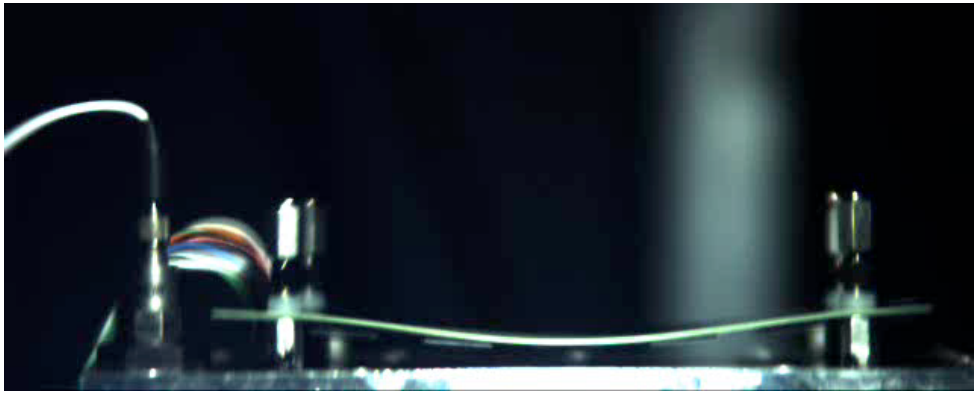
- Advantage:
  - No wires soldered to the test board, no interference with board mechanics
  - Low cost system
- Disadvantages:
  - Cannot test in-situ dynamic response (during board deflection and vibration conditions)
  - Only one test per drop provides fairly poor resolution for when failure occurs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

PWB Loading Conditions

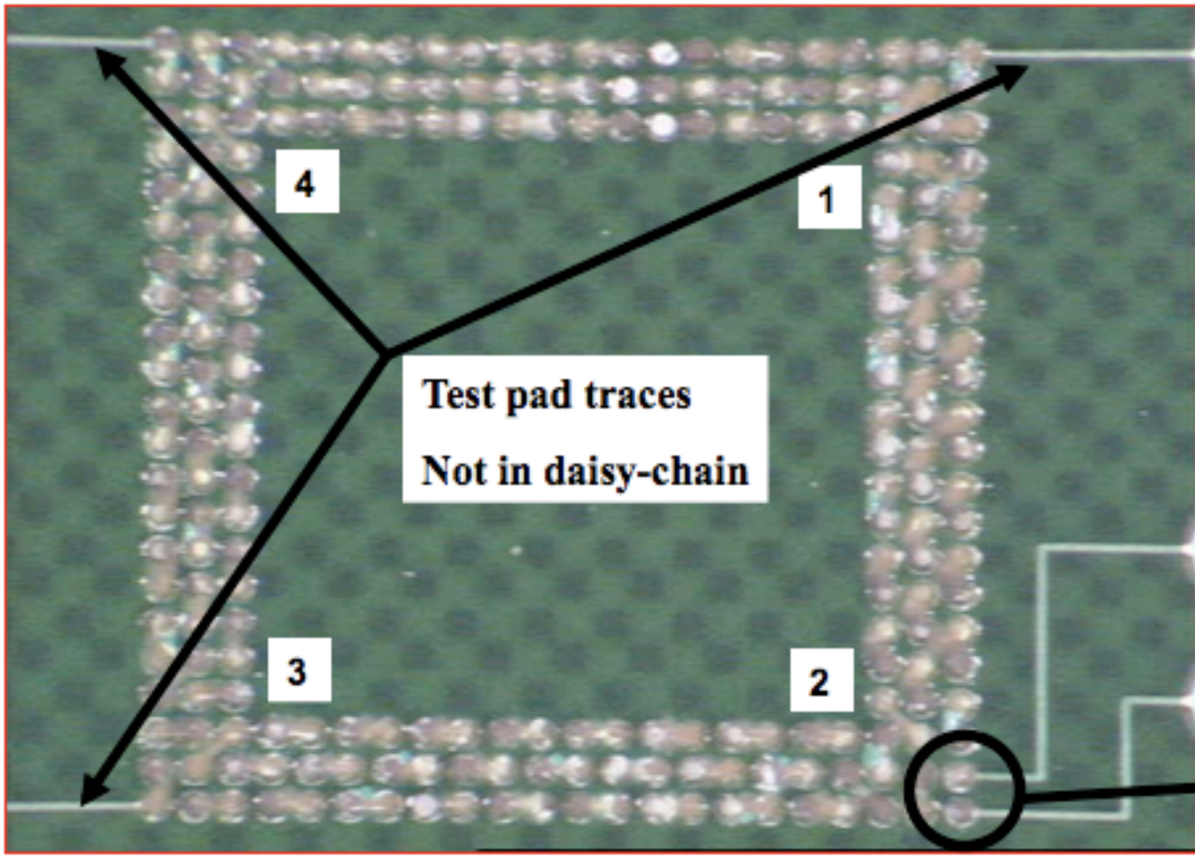
- JEDEC drop testing causes a complex PWB strain condition; not all solder joints experience the same stress and strain
  - Reliability and failure analysis must consider component location, drop count, and acceleration pulse profile



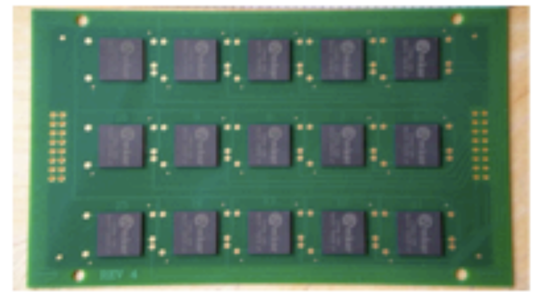
(Image from JEDEC JESD22-B111)



I/O Trace Failure Location



Solder pad layout for the CSP used in the test vehicle, orientation as board below



Cable located to the right

Critical Signal Traces

Area where I/O failure occurs most often

Failure Analysis

- Cross-sectioning with SEM and optical microscopy
- Dye penetrant method with optical microscopy

- Dominant failure modes
  - Trace fracture in board-side copper due to pad cratering
  - Solder fracture near board-side intermetallic layer

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