NASA-DoD Lead-Free Electronics Project

2011 INTERNATIONAL WORKSHOP on ENVIRONMENT and ENERGY

November 18, 2011

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Why Lead-Free Electronics?

- Restriction and elimination of lead (Pb) in electronics products enacted by the European Union
  - Restriction of Hazardous Substances (RoHS) in Electrical and Electronic Equipment; Waste from Electrical and Electronic Equipment (WEEE)] and Pacific-Rim geographical regions (circa 2006).
  - Contribute to the protection of human health and the environmentally sound recovery and disposal of waste electrical and electronic equipment
- Non-U.S. countries continue restricting the disposal of electronic products containing Pb.
- The U.S. does not have existing federal legislation, but several states have adopted laws restricting Pb content in the manufacturing and disposal of electronic equipment.

http://www.trade2save.com/blog/2008/recyling/a-mountain-of-waste-and-suffering-in-guiyu/112/

http://scienceblogs.com/worldsfair/2007/06/what_we_waste_a_view_of_etrash.php

Processes Must Evolve with Technology Changes

The first GPS receiver station developed by Rockwell Collins in 1976.
Images © Rockwell Collins, Inc

GPS Technology Evolution

GPS in 1976 – Hundreds of pounds

GPS in 2009 – One pound

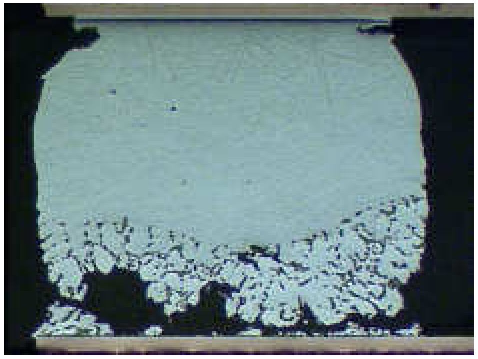
Need

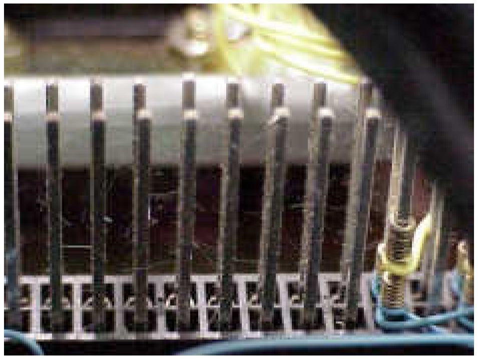
Introduction of lead-free components presents one of the greatest risks to the reliability of military and aerospace electronics.

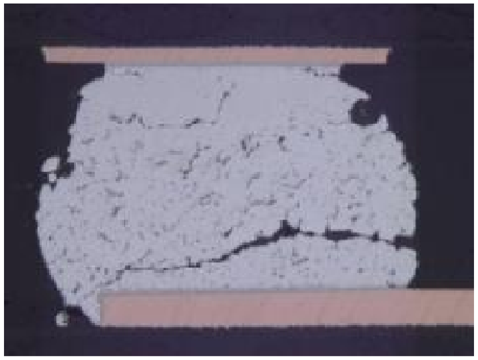
Customers, suppliers, and maintainers of aerospace and military electronic systems now have a host of concerns such as:

- Electrical shorting due to tin whiskers
- Incompatibility of lead-free processes and parameters (including higher melting points of lead-free alloys)
- Unknown properties that can reduce solder joint reliability

It will be critical to fully understand the implications of reworking lead-free assemblies.



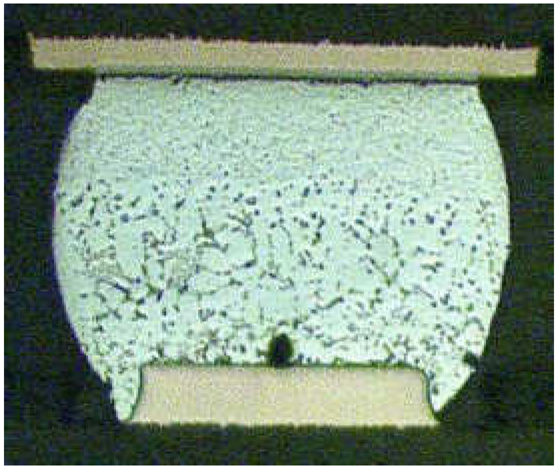
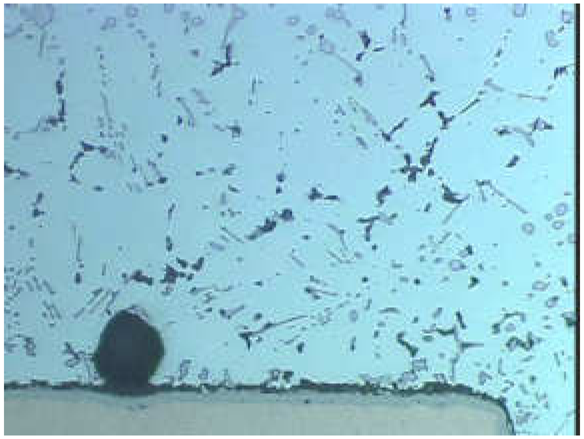




Benefit

One of the largest most comprehensive projects evaluating the reliability of lead-free solder alloys that:

- Focuses on rework of tin-lead and lead-free solder alloys
- Includes mixing of tin-lead/lead-free & lead-free/tin-lead solder alloys during manufacturing and rework.
- Furthers understanding of how lead-free solder interconnects can be designed for and used in high reliability electronic assemblies.

SAC BGA assembled in a conventional SnPb solder process. Failure in temperature cycling (-55 to 125°C) occurred in less than 150 cycles. This type of defect could escape current screening practices.

Resources

Project documents, test plans, test reports and other associated information will be available on the web:

- NASA-DoD Lead-Free Electronics Project:

  http://www.teerm.nasa.gov/projects/NASA_DODLeadFreeElectronics_Proj2.html

  - Joint Test Protocol
  - Project Plan
  - Final Test Reports

Key Project Stakeholders

U.S. AIR FORCE

DEFENSE MICROELECTRONICS ACTIVITY
UNITED STATES OF AMERICA

NASA

NAVSEA
WARFARE CENTERS
CRANE

Rockwell Collins

BAE SYSTEMS

LOCKHEED MARTIN
We never forget who we're working for™

NIHON SUPERIOR

BOEING

Raytheon

CELESTICA

Sandia National Laboratories

GENERAL DYNAMICS
Advanced Information Systems

calce™

Honeywell

HARRIS

TEXAS INSTRUMENTS

COM DEV

Premier
SEMICONDUCTOR SERVICES, LLC

ITB·inc.

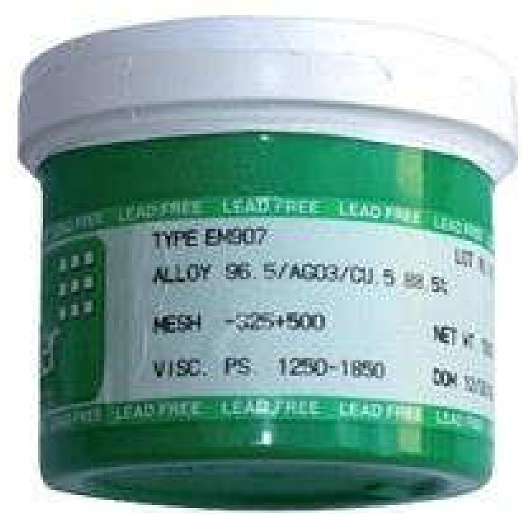
Interconnect PWB Solutions Inc.

Scorpio Solutions

Lead-Free Solder Alloys

SAC305 (Sn3.0Ag0.5Cu)

- ➢ Surface mount assembly
  - ❑ Chosen for reflow soldering because it has shown the most promise as a primary replacement for tin-lead solder.
  - ❑ Serves best as a "general purpose" alloy. {EnviroMark™ 907 from Kester.}



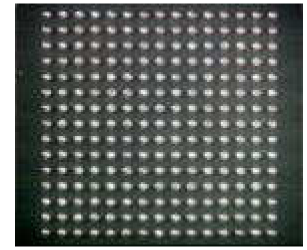
SN100C (Sn0.7Cu0.05Ni+Ge)

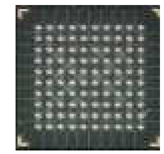
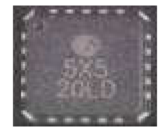
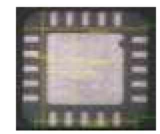
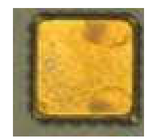
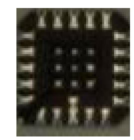
- ➢ Plated through hole
- ➢ Surface mount assembly
  - ❑ This alloy is commercially available.
  - ❑ Due to superior performance, industry is switching to nickel stabilized tin-copper alloy over standard tin-copper.
  - ❑ Does not require special solder pots.

LEAD FREE
NSe®-SOLDER
LEAD FREE SOLDERING

Components

Component Type	Component Finish	Soldering Process	Contact to Printed Circuit Board
BGA-225	SnPb	Reflow Soldering	Solder Balls
	SAC405		
CSP-100	SnPb		
	SAC105		
	SN100C		
QFN-20	Sn		Lands Underneath
	SnPb		
CLCC-20	SAC305		Leadless
	SnPb		
TQFP-144	Sn		Leaded
	SnPb		
	NiPdAu		
	SAC305		
TSOP-50	Sn		
	SnBi		
	SnPb		
PDIP-20	Sn	Wave Soldering	Plated-Through-Hole
	NiPdAu		
	SnPb		



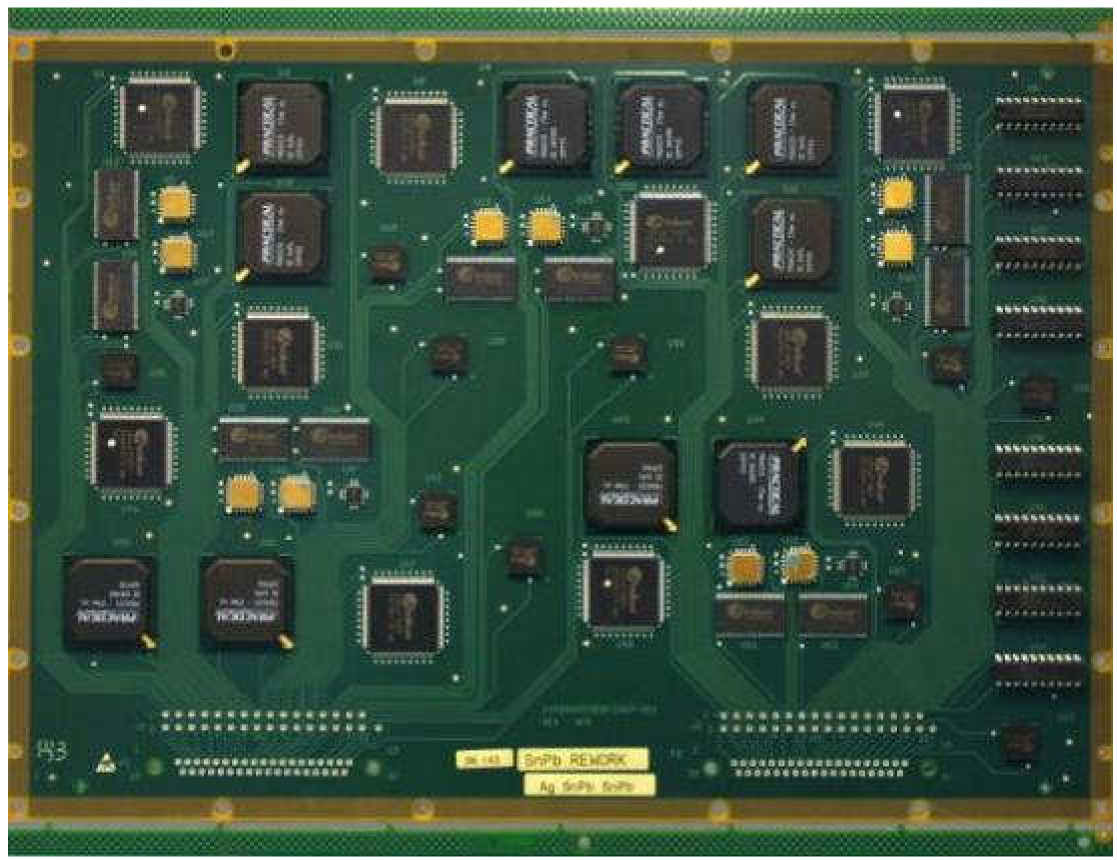








Test Vehicles

Assembled by BAE Systems - Irving, Texas

- ➢ 120 = “Manufactured”
- ➢ 73 = “Rework”
  - ❑ 14.5”X 9”X 0.09”
  - ❑ 6 layers of 0.5 ounce copper
  - ❑ FR4 per IPC-4101/26 with a minimum Tg of 170ºC (Isola 370HR)
  - ❑ Surface Finish
    - Most Immersion Ag
    - Some ENIG

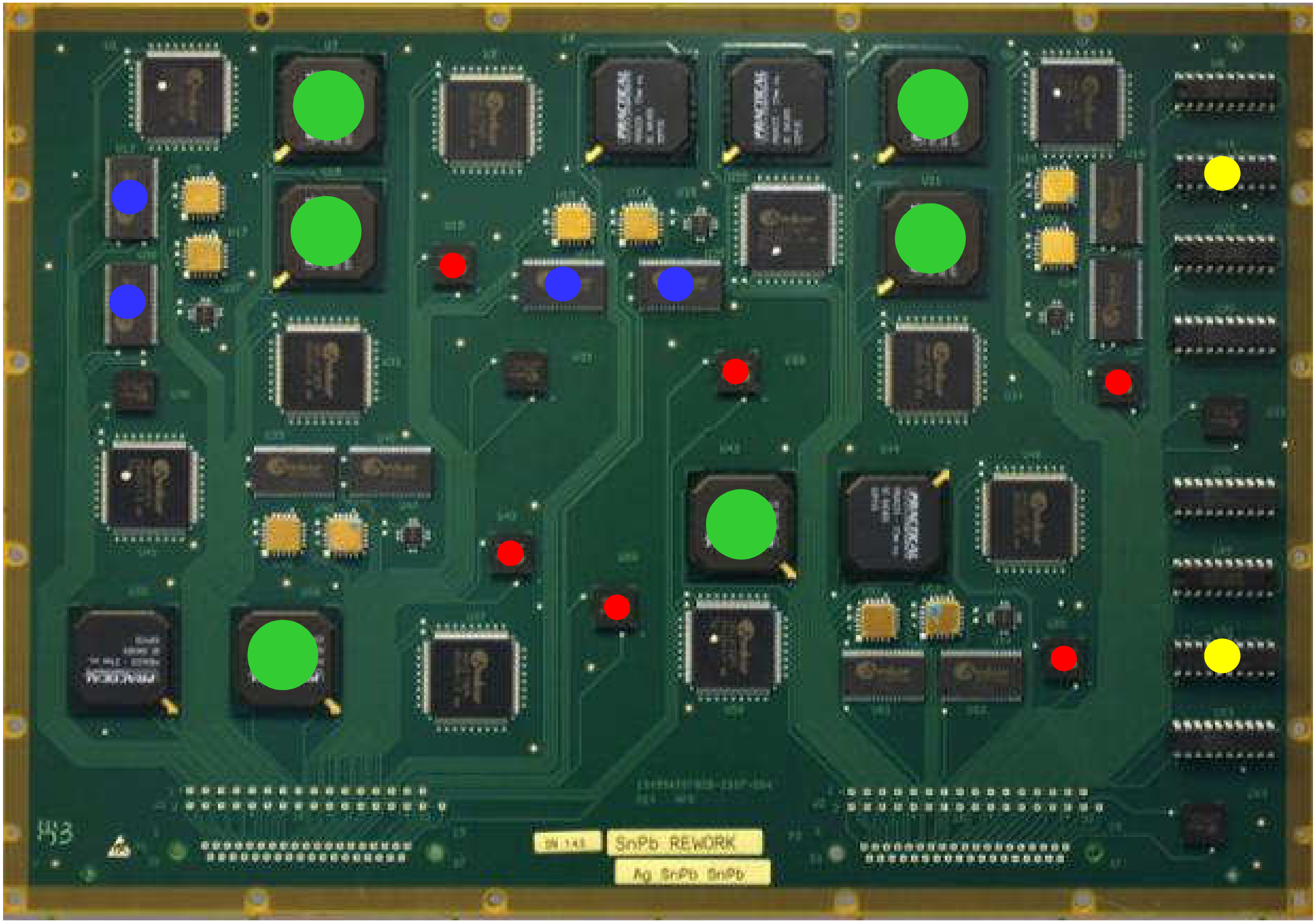


Test Vehicles

Solder alloy combinations generated during initial assembly

Solder Alloy	Component Finish: SAC405	SAC305	SAC305 Dip	SAC105	SN100C	NiPdAu	SnBi	Sn	Matte Sn	SnPb	SnPb Dip
SAC305	BGA	CLCC	TQFP	CSP		TQFP	TSOP	TSOP	QFN TQFP	BGA CLCC CSP QFN TSOP	TQFP
SN100C	BGA	CLCC		CSP	CSP	PDIP	TSOP	PDIP TSOP	QFN TQFP	BGA CLCC CSP TSOP	TQFP
SnPb	BGA	CLCC		CSP		PDIP TQFP	TSOP	PDIP TSOP	QFN TQFP	BGA CLCC CSP PDIP QFN TSOP	TQFP

“Rework” Test Vehicles



Reworked Components

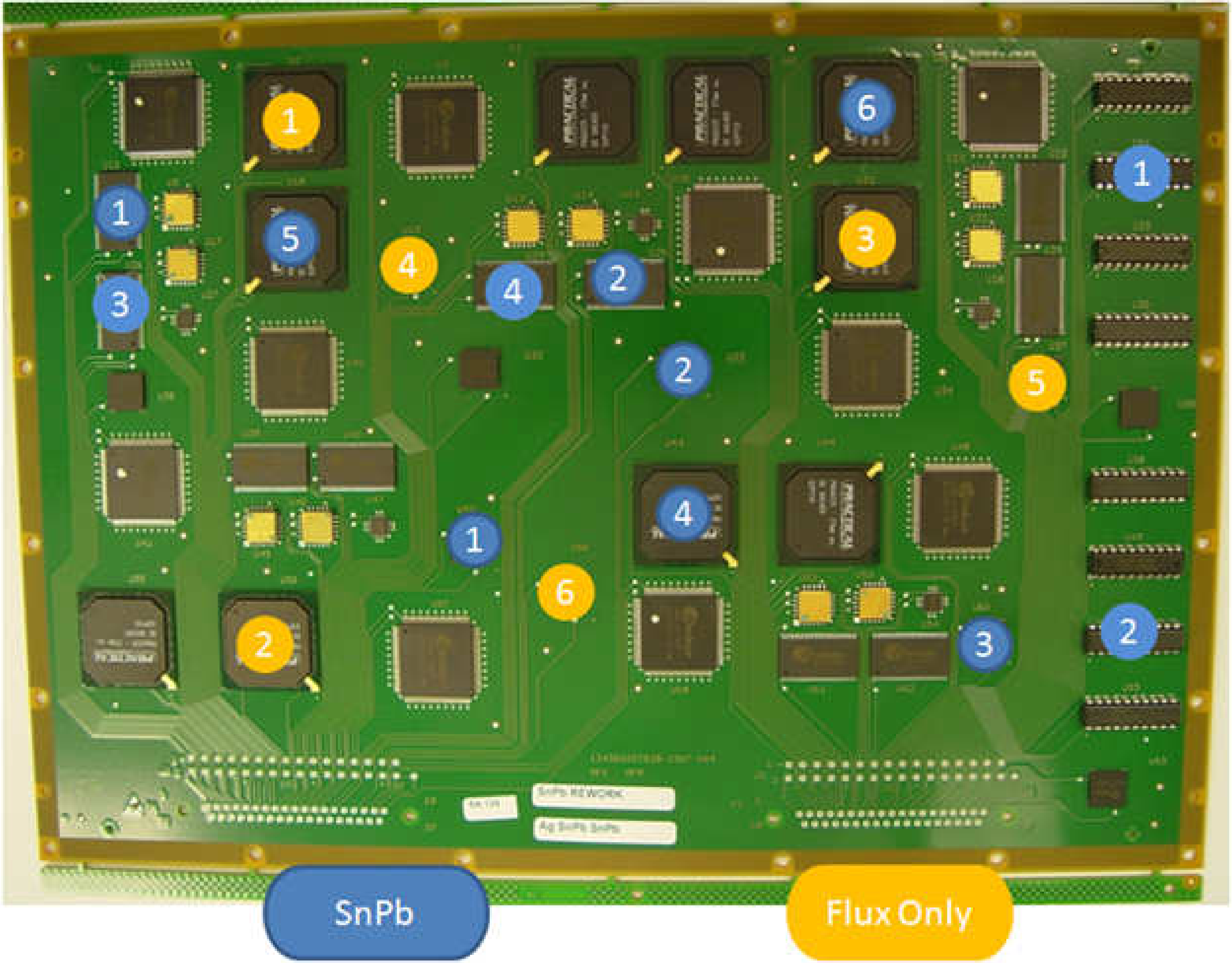
U18 – BGA-225
U43 – BGA-225
U06 – BGA-225
U02 – BGA-225
U21 – BGA-225
U56 – BGA-225

U33 – CSP-100
U50 – CSP-100
U19 – CSP-100
U37 – CSP-100
U42 – CSP-100
U60 – CSP-100

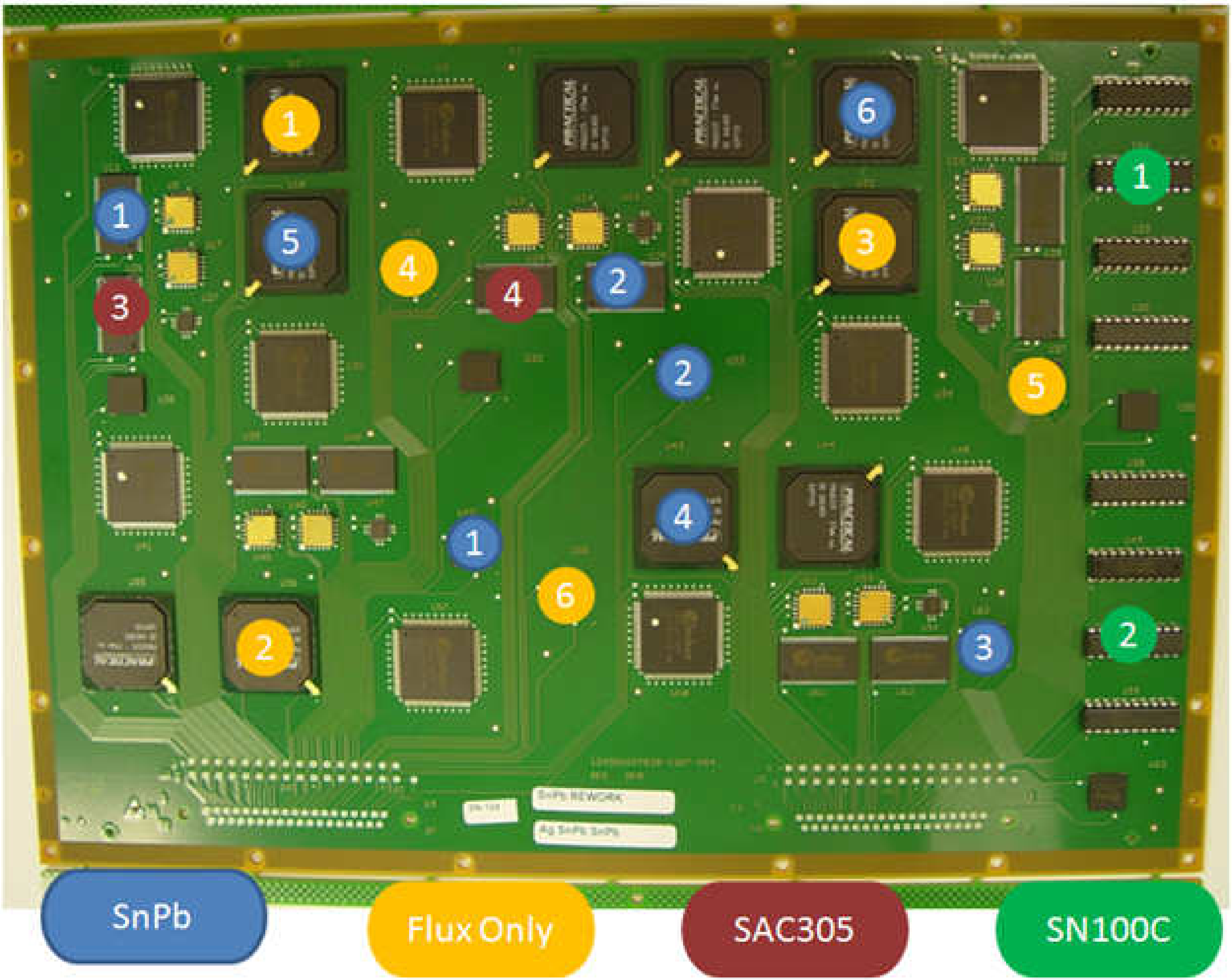
U11 – PDIP-20
U51 – PDIP-20

U12 – TSOP-50
U25 – TSOP-50
U24 – TSOP-50
U26 – TSOP-50

Rework Procedure – SnPb Rework



Rework Procedure – Lead-Free Rework



Testing

- Thermal Cycle Testing (-20/+80°C) BOEING
- Combined Environments Testing Raytheon
- Drop Testing CELESTICA
- Thermal Cycle Testing (-55/+125°C) Rockwell Collins
- Vibration Testing BOEING CELESTICA
- Mechanical Shock Testing BOEING

Thermal Cycling -20º / 80ºC

- Approximately 13,500 cycles have been completed.
- Hopefully the thermal chamber will be allowed to operate until at least 17,000 thermal cycles have been completed.

- Phase I LF BGA-225 data

		Component Finish	Solder Paste	90	91	92	93	94
U4	BGA-225	SnAgCu	Sn3.9Ag0.6Cu	20615	21390	16564	19551	21052
U6	BGA-225	SnAgCu	Sn3.9Ag0.6Cu	17157	25813	15709	18638	14185
U18	BGA-225	SnAgCu	Sn3.9Ag0.6Cu	21152	25233	20572	26624	19694
U43	BGA-225	SnAgCu	Sn3.9Ag0.6Cu	17875	22063	21359	14648	14857
U55	BGA-225	SnAgCu	Sn3.9Ag0.6Cu	21132	26216	21714	19344	16059
			Total Cycles		27,135			

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Combined Environments Test

- Overall, the component type had the greatest effect on solder joint reliability performance.
- Of the surface mount technology, the BGA-225 components performed the worst.
- In general, tin-lead finished components soldered with tin-lead solder paste were the most reliable.

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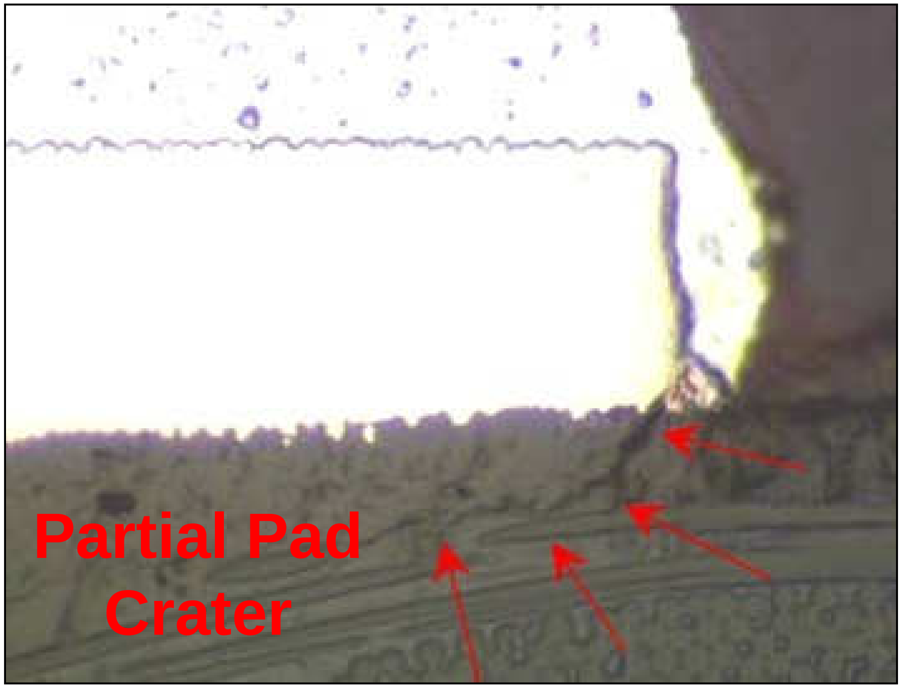
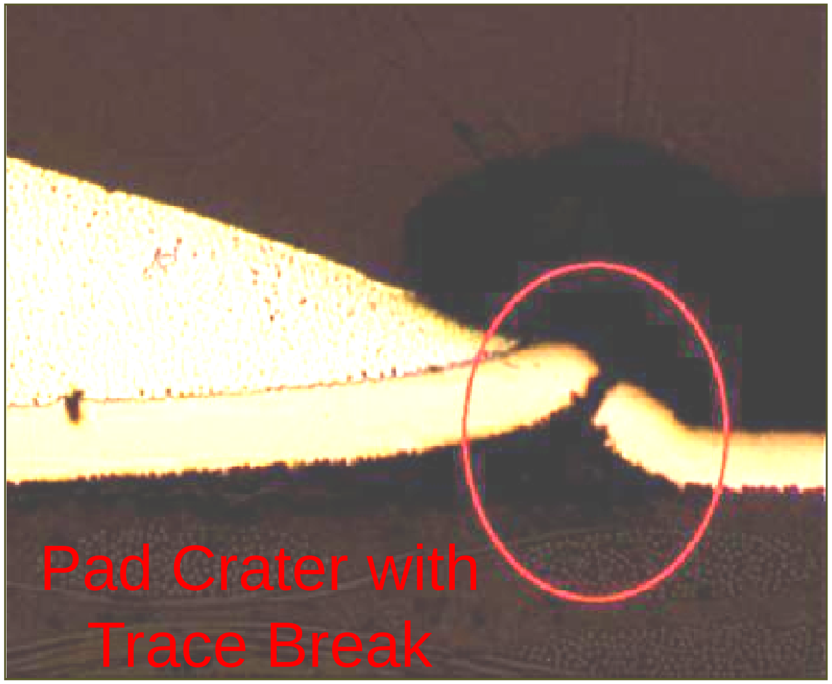
Drop Testing

- It was found that the drop test reliability greatly depends on the component type.
- The only component type to show a significant number of electrical failures during this test were the BGAs. The BGA-225 electrical failures mostly occurred at or near the corner joints.
- The predominant damage mechanism in drop testing is pad cratering. Cracks propagate through the board material between the laminate and glass fiber under the pads.





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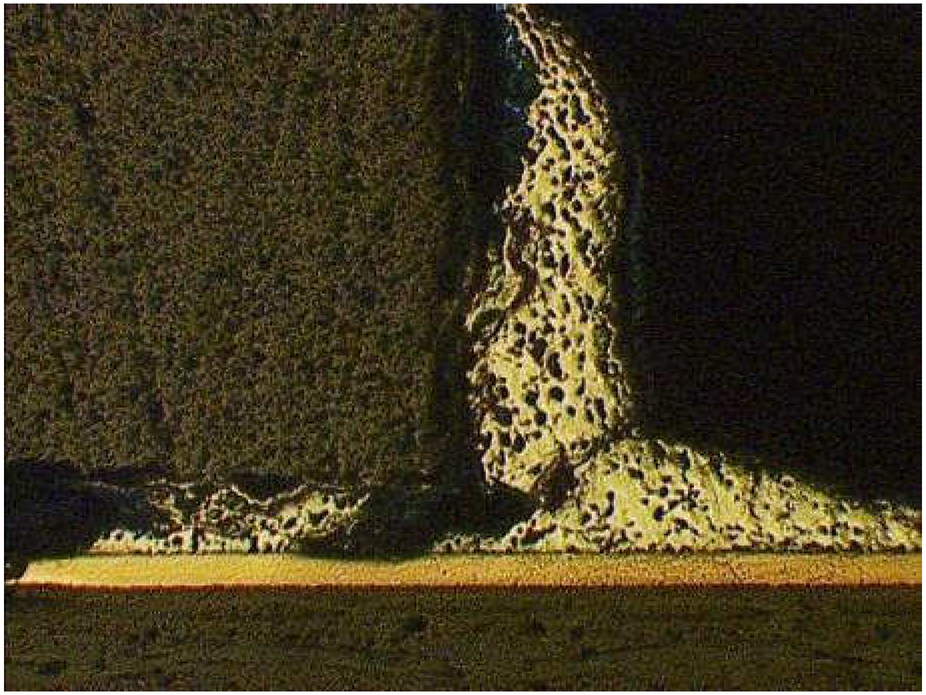
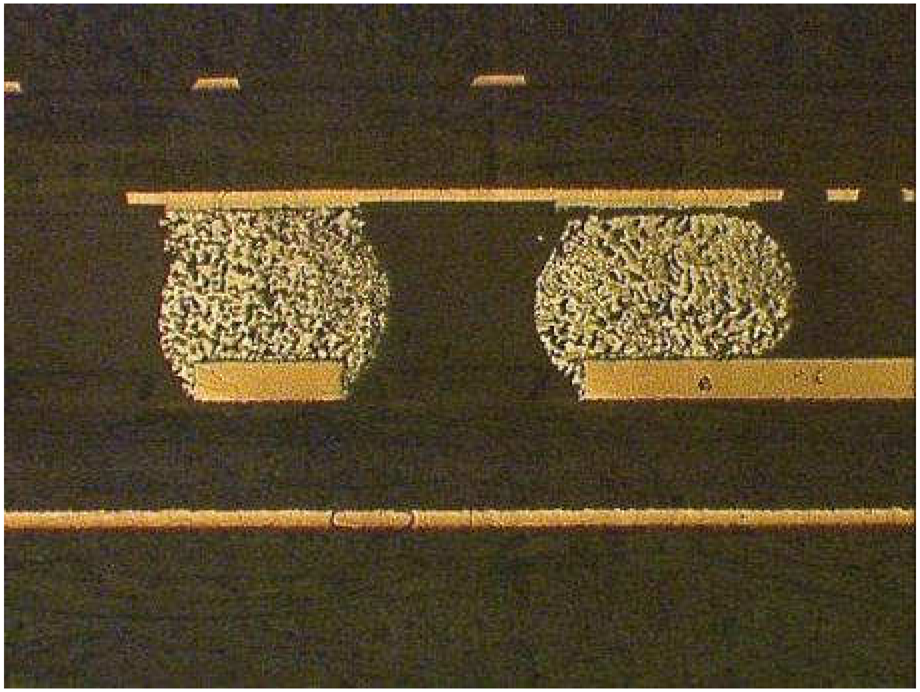
Thermal Cycle Testing (-55/+125°C)

- Completed 4,068 thermal cycles
  - Initial Analysis = In general, the preliminary results show that the SnPb solder alloy out performed the two lead-free solder alloys in many cases.
  - However, the performance of the lead-free solder alloys was not without merit. The question to be answered is: "How good is good enough for a product application?"



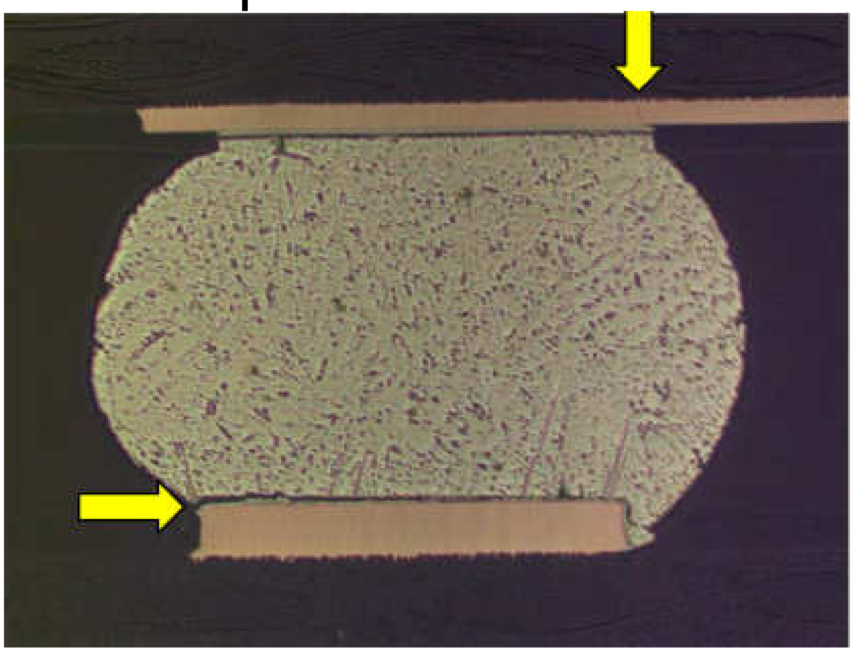


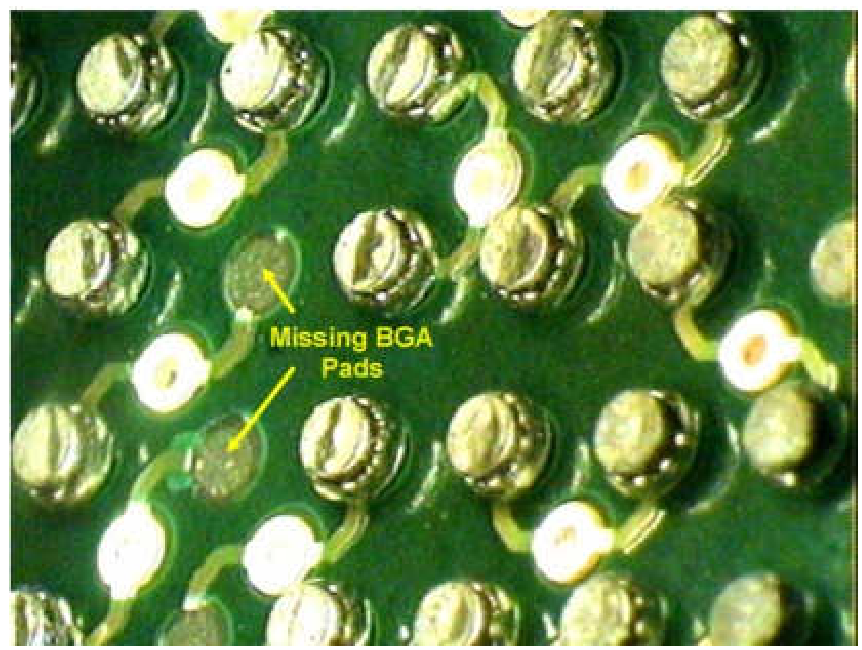
Testing

- Thermal Cycle Testing (-20/+80^{o}C)
- Combined Environments Testing
- Drop Testing
- Thermal Cycle Testing (-55/+125^{o}C)
- Vibration Testing
- Mechanical Shock Testing

Vibration Testing

- The results of this study suggest that for many component types, the lead-free solders tested are not as reliable as eutectic SnPb solder with respect to vibration. Rework also had a negative effect on both SnPb and lead-free solders with respect to vibration.
- For severe vibration environments, the use of lead-free solders may require the use of stiffeners, bumpers, or vibration isolators to reduce PWA flexure and reduce solder joint strains to acceptable levels.





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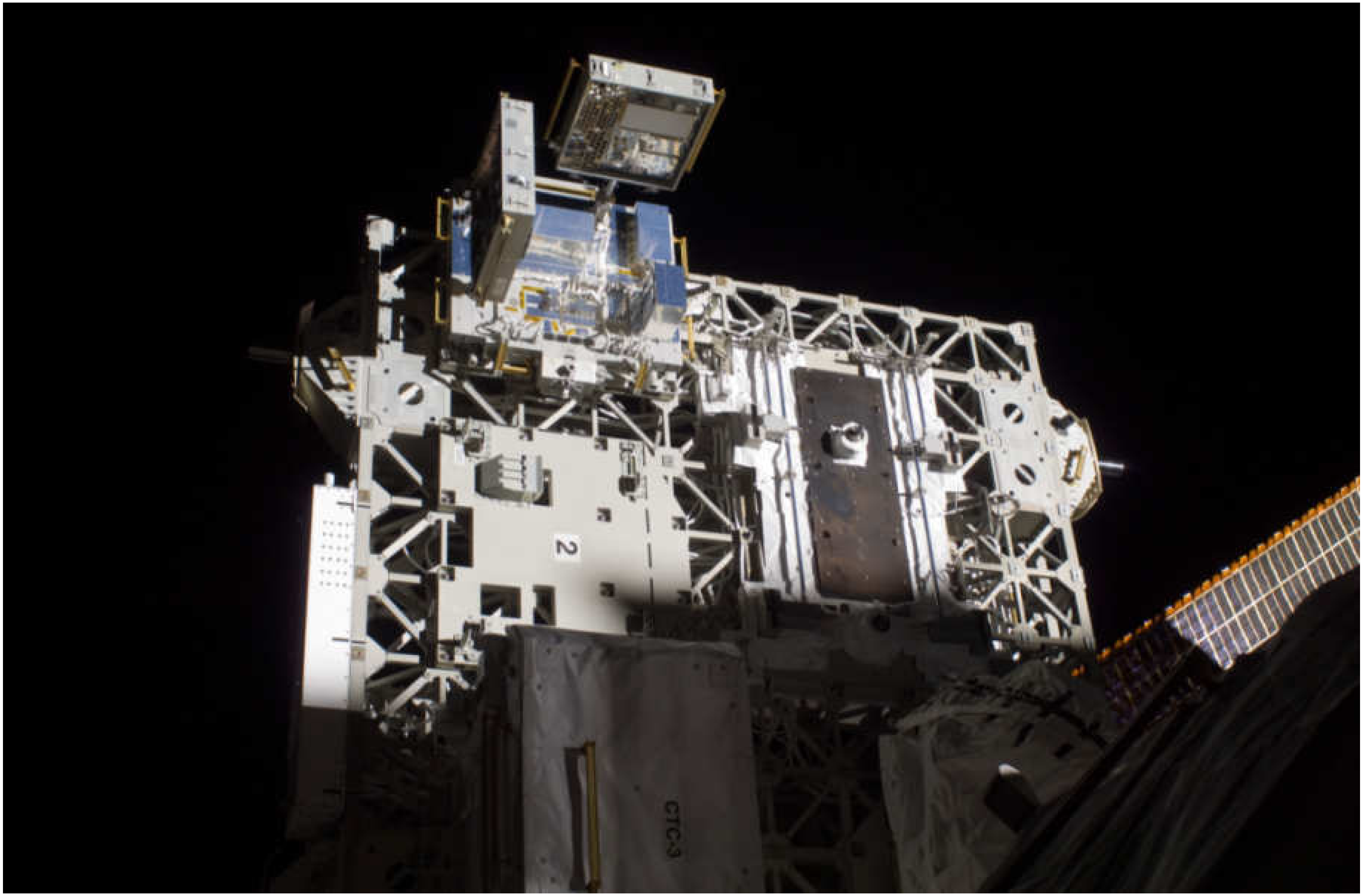
Mechanical Shock Testing

- In general, the pure lead-free systems (SAC305/SAC405 balls, SAC305/SAC105 balls, SAC305/Sn, and SN100C/Sn) performed as well or better than the SnPb controls (SnPb/SnPb or SnPb/Sn).
- Many of the BGA failures (SnPb/SbPb balls, SAC305/SAC405 balls, and mixed technologies) were due to pad cratering. This suggests that board laminates may be the weakest link for large area array components.
- It should be noted that all of the surface mount components survived 100 shock pulses at each of the first three test levels {per *MIL-STD-810G, Method 516.6*}. This means that they effectively passed:
  - Functional Test for Flight Equipment 33 times
  - Functional Test for Ground Equipment 33 times
  - Crash Hazard Test for Ground Equipment 33 times

Lead-free Technology Experiment in Space Environment (LTESE)



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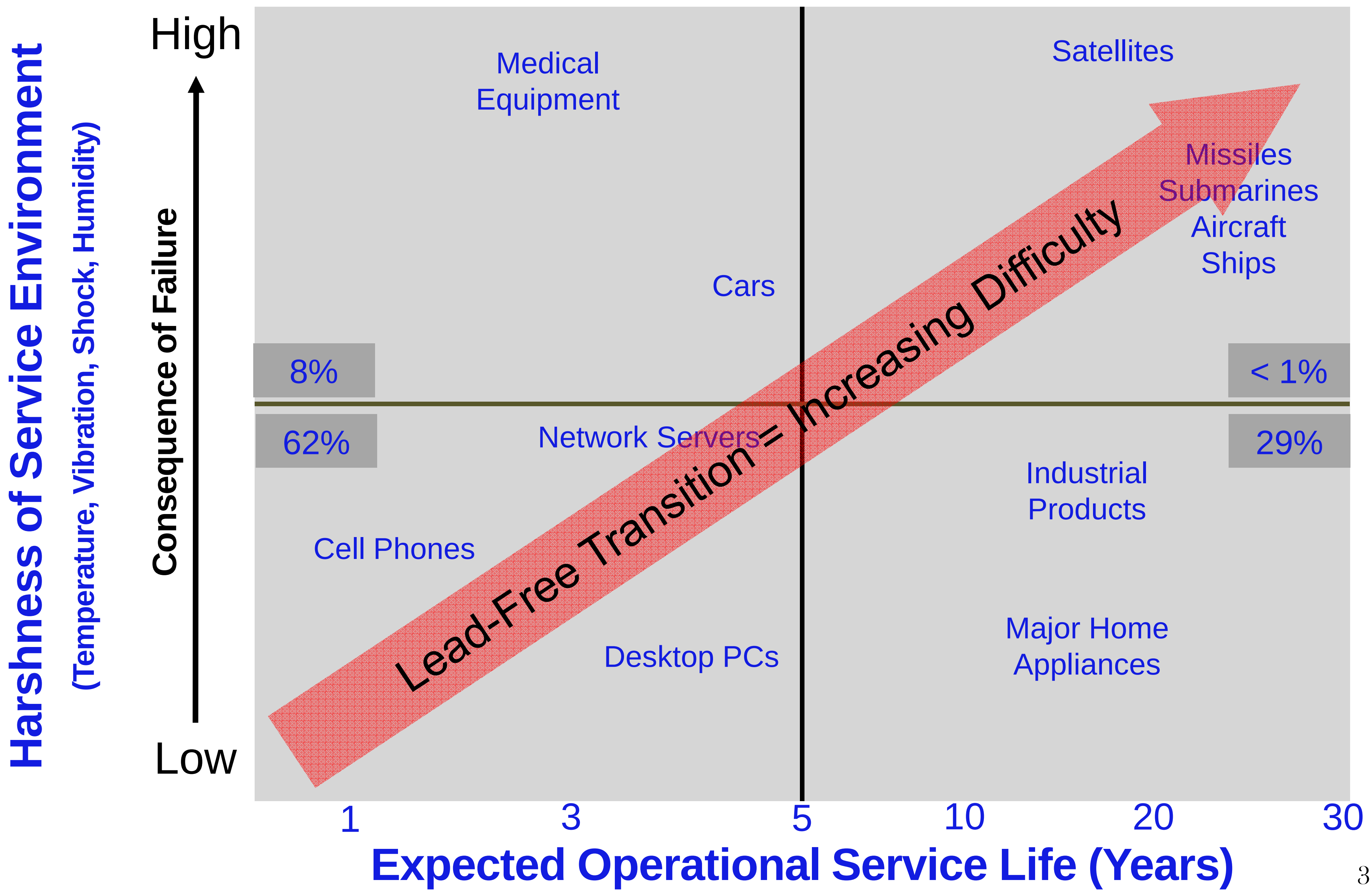
FERGUSON HURLEY MAGNUS WALHEIM
STS 135


United States

Back Up Slides

Military and Aerospace sectors have little influence on the global transition to Lead-Free (<1% Market Share)



Test Vehicles

Assembly Details - SnPb

- Reflow Soldering
- Location – BAE Systems Irving, Texas
- Reflow Profile = SnPb
  - Preheat = ~ 120 seconds @140-183℃
  - Solder joint peak temperature = 225℃
  - Time above reflow = 60-90 sec
  - Ramp Rate = 2-3 ℃/sec

- Wave Soldering
- Location – BAE Systems Irving, Texas
- Wave Profile = SnPb
  - Solder Pot Temperature = 250℃
  - Preheat Board T = 101℃
  - Peak Temperature = 144℃
  - Speed: 110 cm/min

Assembly Details – Lead-Free

- Reflow Soldering
- Location – BAE Systems Irving, Texas
- Reflow Profile = SAC305
  - Preheat = 60-120 seconds @150-190℃
  - Peak temperature target = 243℃
  - Reflow:~20 seconds above 230℃
  - ~30-90 seconds above 220℃

- Wave Soldering
- Location – Scorpio Solutions
- Wave Profile = SN100C
  - Solder Pot Temperature = 265℃
  - Preheat Board T = 134℃
  - Peak Temperature = 155℃ to 175℃
  - Speed: 90 cm/min

Test Vehicles

Batch	Test Vehicle Type	Reflow Solder	Wave Solder
A	Lead-Free Rework All Test Vehicles	SAC305	SN100C
B	SnPb Rework* All Test Vehicles	SnPb*	SnPb*
C	SnPb Manufactured Test Vehicles Thermal Cycle and Combined Environments	SnPb	SnPb
D	SnPb Manufactured Test Vehicles Vibration, Mechanical Shock and Drop	SnPb	SnPb
E	Lead-Free Manufactured Test Vehicles Thermal Cycle and Combined Environments	SAC305	SN100C
F	Lead-Free Manufactured Test Vehicles Vibration, Mechanical Shock and Drop	SAC305	SN100C
G	Lead-Free Manufactured Test Vehicles Thermal Cycle and Combined Environments	SN100C	SN100C
H	Lead-Free Manufactured Test Vehicles Vibration, Mechanical Shock and Drop	SN100C	SN100C
I	Lead-Free Manufactured Test Vehicles Crane Rework Effort	SN100C	SN100C

* NOTE: Lead-Free profiles will be used for reflow and wave soldering

Component Finish/Solder Combinations

SnPb Rework

Lead-Free components introduced into a SnPb assembly

RefDes	Component	Original Component Finish	Reflow Solder	Wave Soldedr	New Component Finish	Rework Solder
U18	BGA-225	SnPb	SnPb		SAC405	SnPb
U43	BGA-225	SnPb	SnPb		SAC405	SnPb
U06	BGA-225	SnPb	SnPb		SAC405	SnPb
U02	BGA-225	SnPb	SnPb		SnPb	Flux Only
U21	BGA-225	SnPb	SnPb		SnPb	Flux Only
U56	BGA-225	SnPb	SnPb		SnPb	Flux Only
U33	CSP-100	SnPb	SnPb		SAC105	SnPb
U50	CSP-100	SnPb	SnPb		SnPb	Flux Only
U19	CSP-100	SnPb	SnPb		SnPb	Flux Only
U37	CSP-100	SnPb	SnPb		SnPb	Flux Only
U42	CSP-100	SnPb	SnPb		SAC105	SnPb
U60	CSP-100	SnPb	SnPb		SAC105	SnPb
U11	PDIP-20	SnPb		SnPb	Sn	SnPb
U51	PDIP-20	SnPb		SnPb	Sn	SnPb
U12	TSOP-50	SnPb	SnPb		SnPb	SnPb
U25	TSOP-50	SnPb	SnPb		SnPb	SnPb
U24	TSOP-50	SnPb	SnPb		Sn	SnPb
U26	TSOP-50	SnPb	SnPb		Sn	SnPb

Component Finish/Solder Combinations

Lead-Free Rework

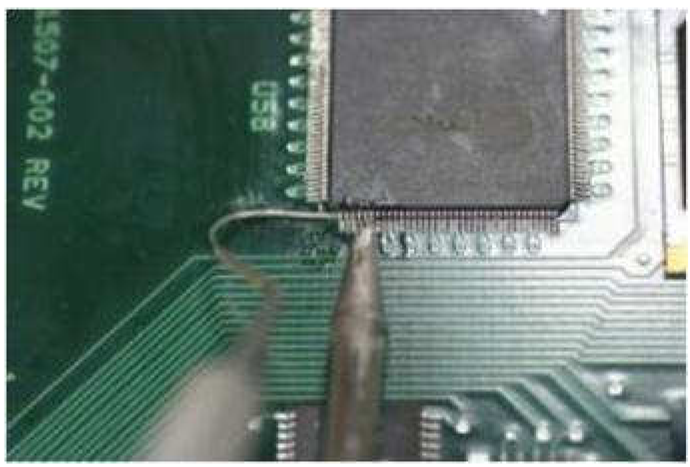
SnPb solder introduced into a lead-free assembly

RefDes	Component	Original Component Finish	Reflow Solder	Wave Solder	New Component Finish	Rework Solder
U18	BGA-225	SAC405	SAC305		SAC405	SnPb
U43	BGA-225	SAC405	SAC305		SAC405	SnPb
U06	BGA-225	SAC405	SAC305		SAC405	SnPb
U02	BGA-225	SAC405	SAC305		SAC405	Flux Only
U21	BGA-225	SAC405	SAC305		SAC405	Flux Only
U56	BGA-225	SAC405	SAC305		SAC405	Flux Only
U33	CSP-100	SAC105	SAC305		SAC105	SnPb
U50	CSP-100	SAC105	SAC305		SAC105	Flux Only
U19	CSP-100	SAC105	SAC305		SAC105	Flux Only
U37	CSP-100	SAC105	SAC305		SAC105	Flux Only
U42	CSP-100	SAC105	SAC305		SAC105	SnPb
U60	CSP-100	SAC105	SAC305		SAC105	SnPb
U11	PDIP-20	Sn		SN100C	Sn	SN100C
U51	PDIP-20	Sn		SN100C	Sn	SN100C
U12	TSOP-50	Sn	SAC305		Sn	SnPb
U25	TSOP-50	Sn	SAC305		Sn	SnPb
U24	TSOP-50	SnBi	SAC305		SnBi	SAC305
U26	TSOP-50	SnBi	SAC305		SnBi	SAC305

NAVSEA Crane Rework Effort

Built 30 test vehicles (sub-set of the 193 assembled)

- Test vehicles were built with Lead-Free solder and Lead-Free component finishes only = similar to Manufactured test vehicles for Mechanical Shock, Vibration and Drop Testing
- Lead-Free alloys, SAC305 and SN100C
- Rework was done using only SnPb solder
- Performed multiple pass rework 1 to 2 times on random lead-free DIP, TQFP-144, TSOP-50, LCC and QFN components
- *<u>Represents real world scenario for deployed Navy vessels</u>*
- Testing
  - Thermal Cycling -55℃ to +125℃
    Rockwell Collins
  - Vibration Testing
    CELESTICA
  - Drop Testing
    CELESTICA



Testing

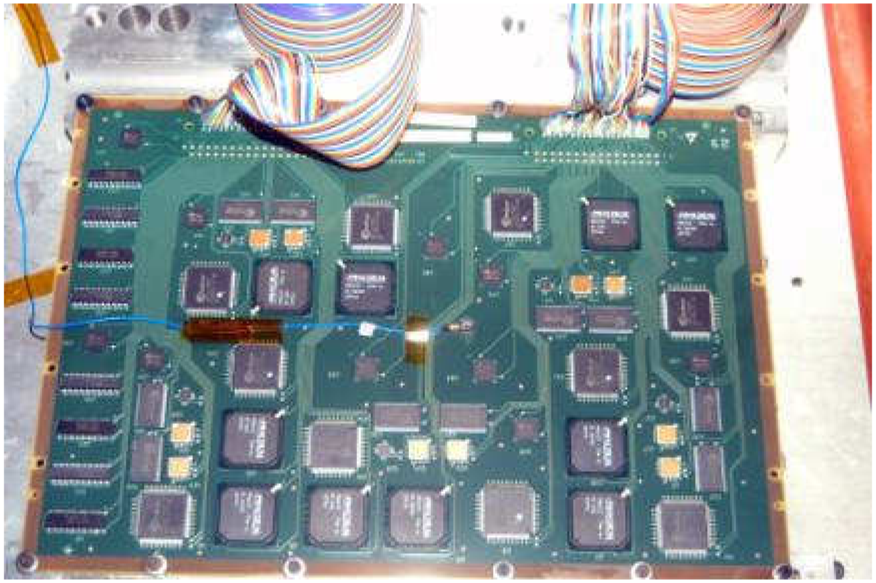
- Thermal Cycle Testing (-20/+80^{o}C)
- Combined Environments Testing
- Drop Testing
- Thermal Cycle Testing (-55/+125^{o}C)
- Vibration Testing
- Mechanical Shock Testing

Thermal Cycling -20º / 80ºC

- 5 to 10ºC/minute ramp
- 30 minute dwell at 80ºC
- 10 minute dwell at -20ºC
- Completed about 13,500 cycles

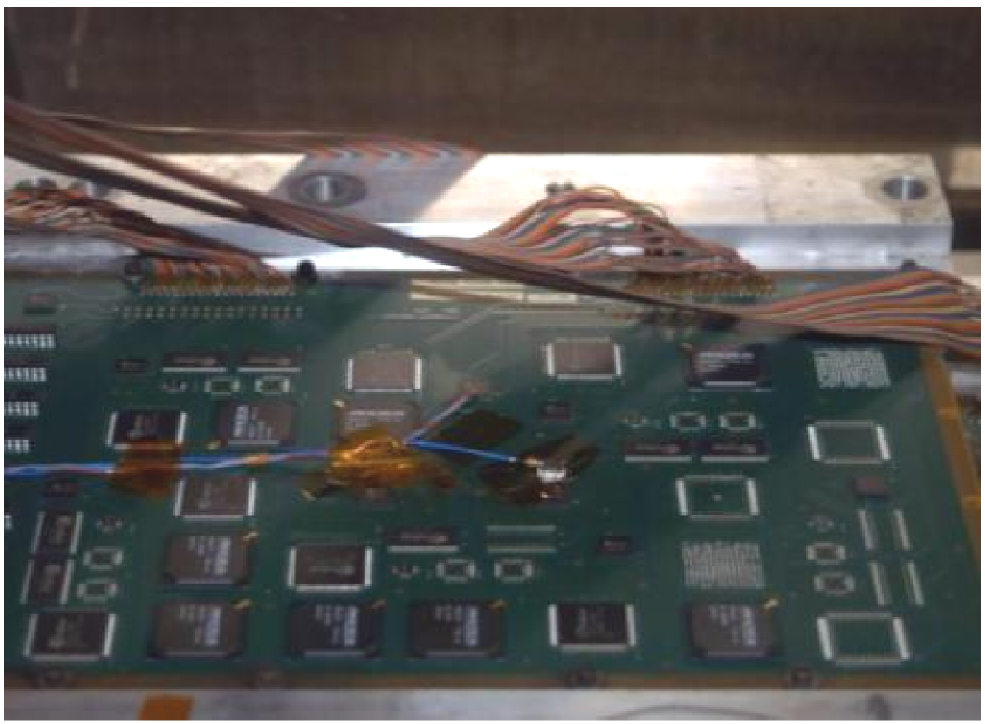
Combined Environments Test

- -55°C to +125°C
- 20°C/minute ramp
- 15 minute dwell at -55°C and +125°C
- Vibration for the duration of the thermal cycle
- 10 g_{rms} pseudo-random vibration initially
- Increase vibration level 5 g_{rms} after every 50 cycles
- 55 g_{rms} maximum



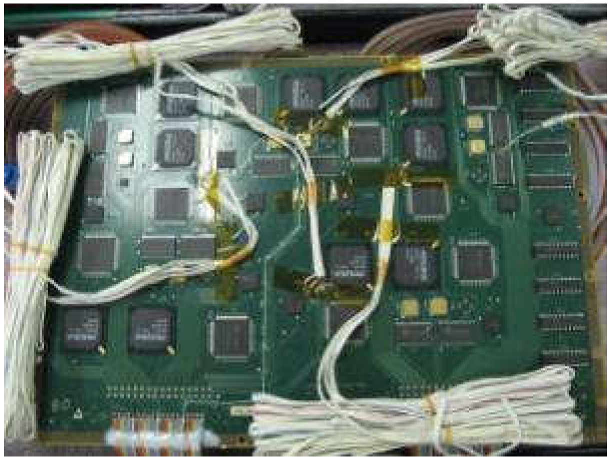
Combined Environments Test

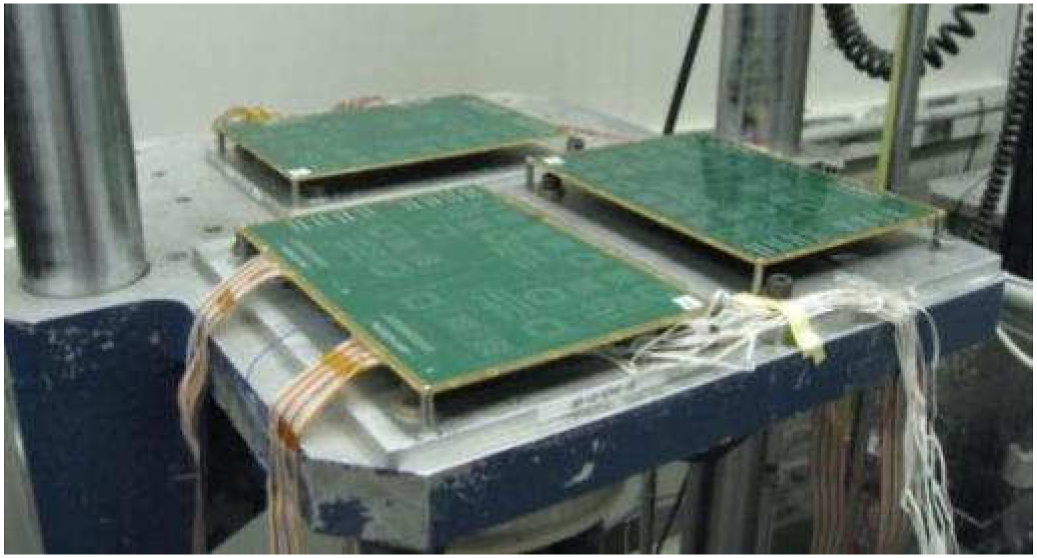
- In general, SAC305 soldered components were less reliable than the tin-lead soldered controls.
- Consideration for high reliability electronics: In several cases, SAC305 solder performed statistically as good as or equal to the baseline, tin-lead solder.

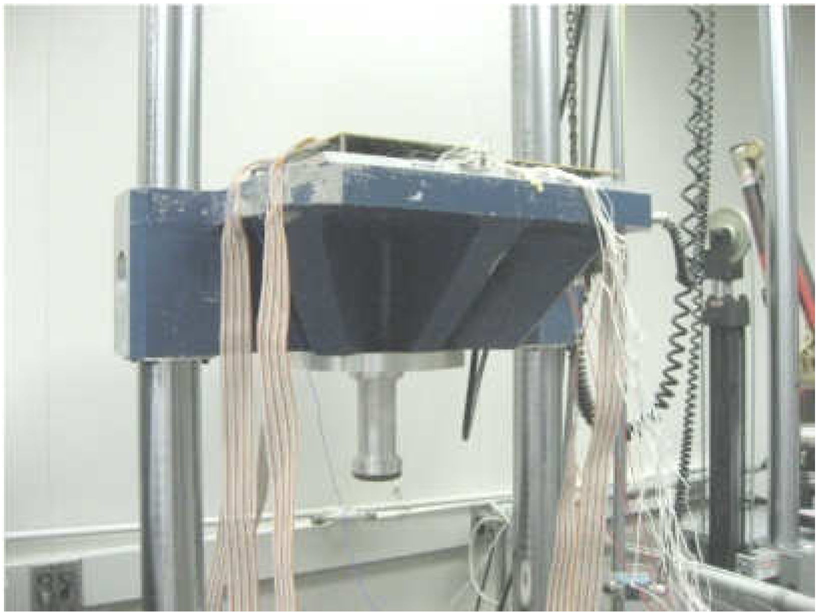


Drop Testing - NSWC Crane Test Vehicles

- Shock parameters: 500 G, 2.0 ms duration (340 G for cards 80, 82, 87 for first 10 drops)
- Number of drops: 20
- 9 cards in total / 3 cards tested per drop
- Each card monitored for shock response
- Each card monitored for resistance
- Cards 80, 83, 86 monitored for strain

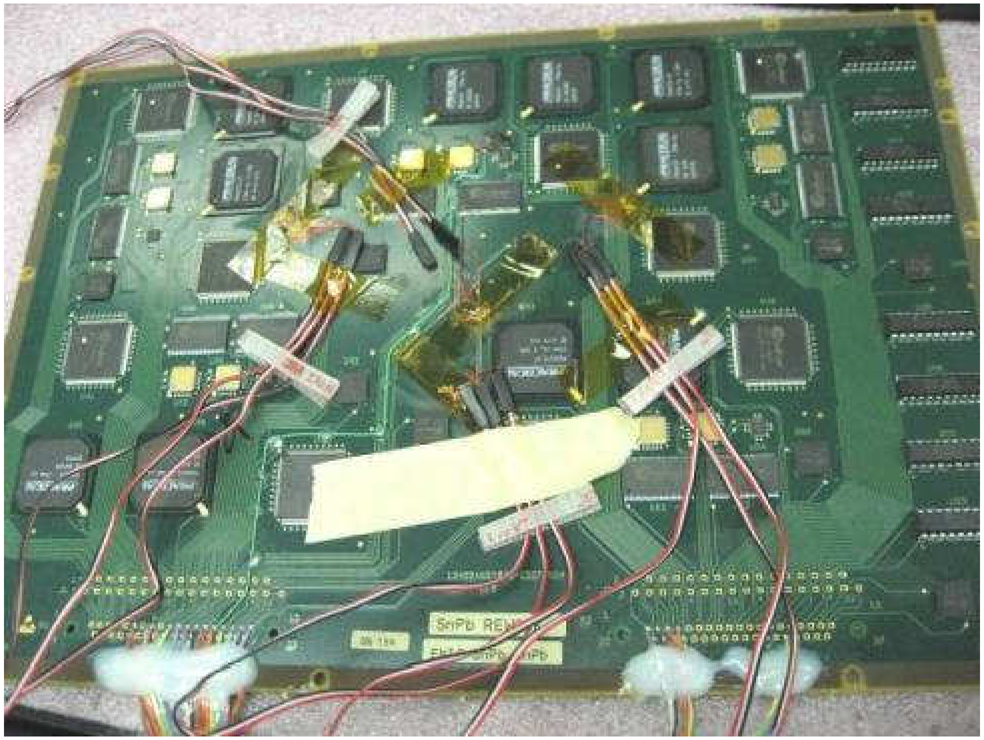


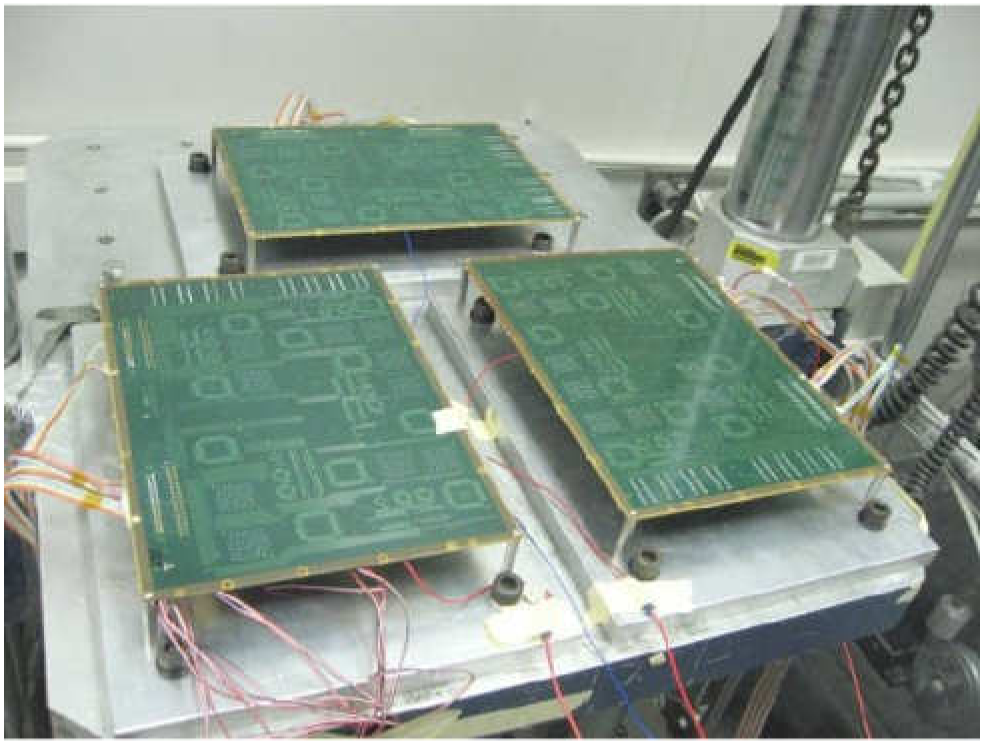




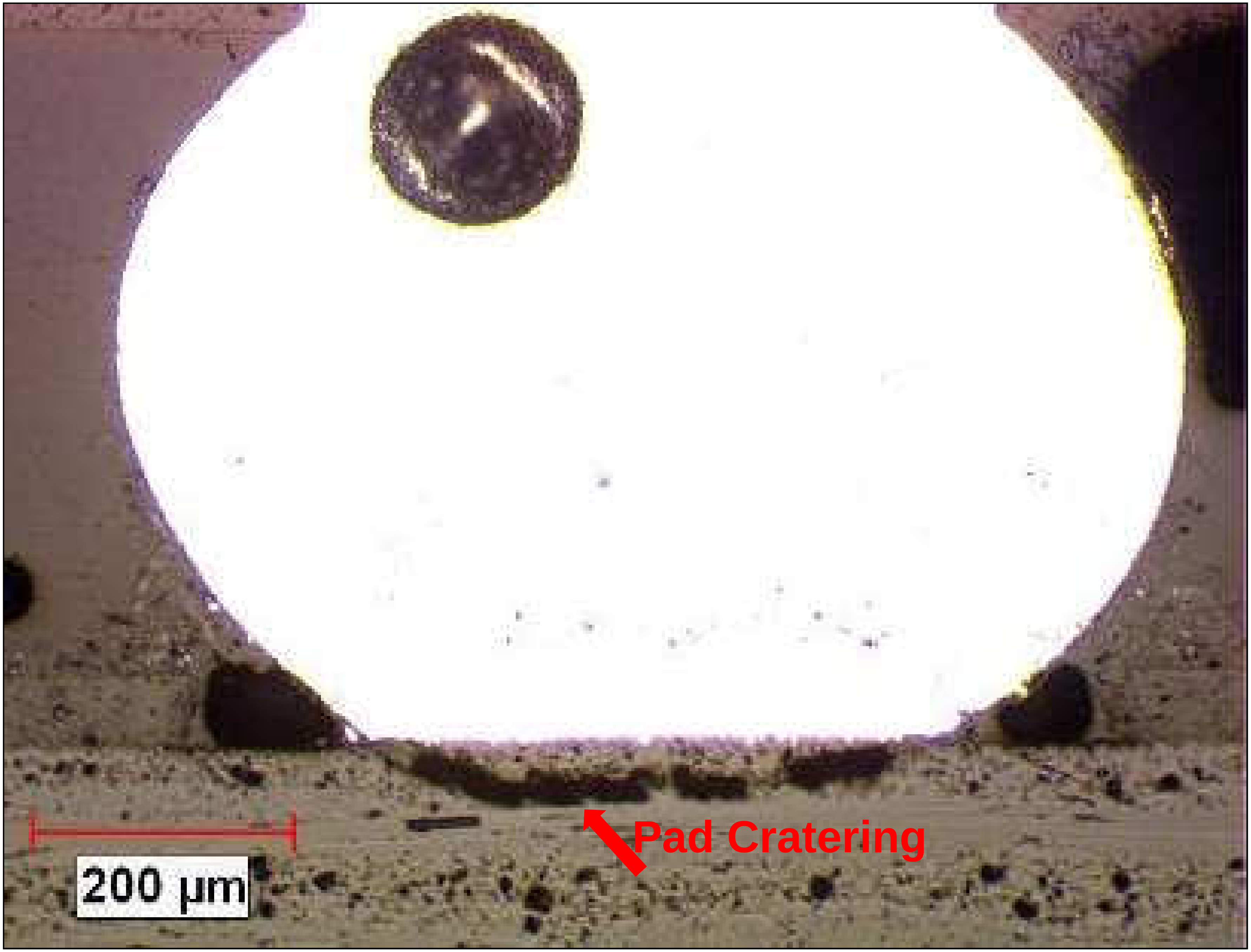
Drop Testing - NASA-DoD Test Vehicles

- Shock testing conducted in the Z - axis
- 500Gpk input, 2ms pulse duration
- Test vehicles dropped until all monitored components fail or 10 drops completed



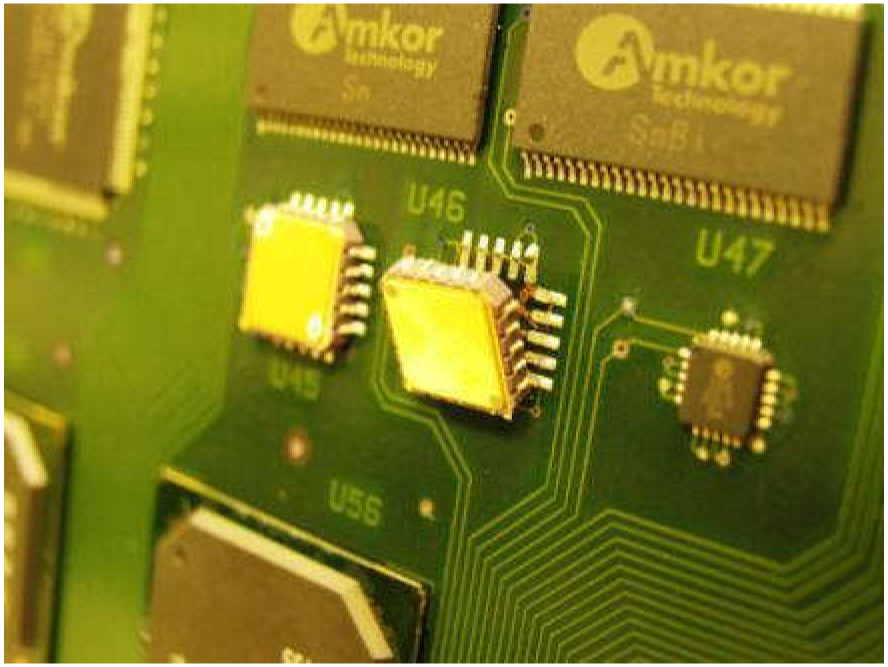


Drop Testing



Thermal Cycle Testing (-55/+125°C)

- 5 to 10°C/minute ramp
- 30 minute dwell at 125°C
- 10 minute dwell at -55°C
- Completed 4,068 thermal cycles



Thermal Cycle Testing (-55/+125°C)

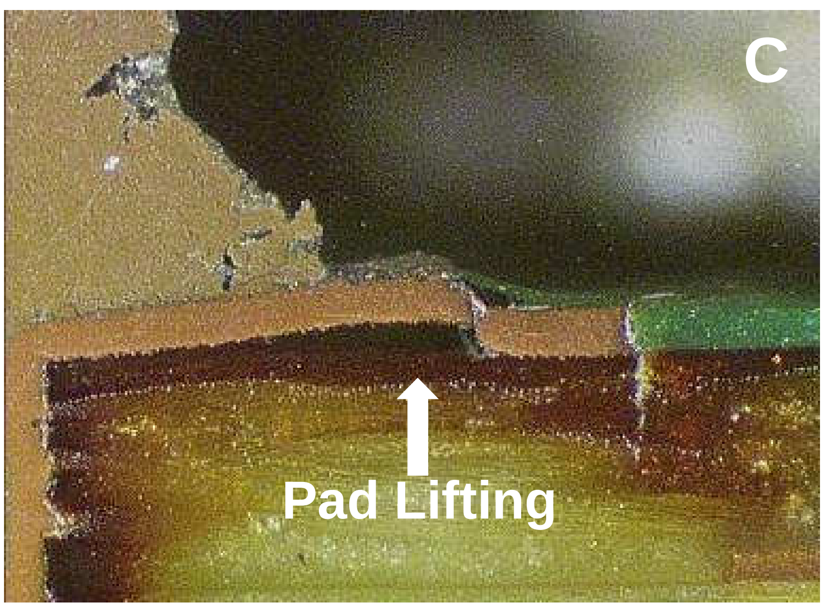
Manufactured Test Vehicles – Failure Rates

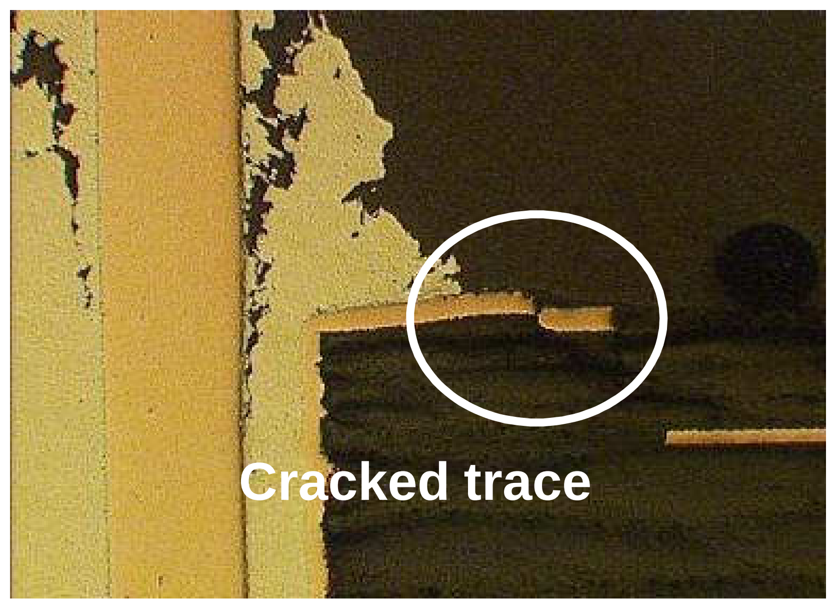
Component Type	Total Failures	Population	Percent Failed
CLCC-20	309	311	99%
QFN-20	88	134	66%
QFP-144	306	309	99%
PBGA-225	253	279	91%
PDIP-20	189	220	86%
CSP-100	252	281	90%
TSOP-50	249	249	100%

Rework Test Vehicles – Failure Rates

Component Type	Total Failures	Population	Percent Failed
PBGA-225	51	66	77%
PDIP-20	57	60	95%
CSP-100	45	67	67%
TSOP-50	99	99	100%

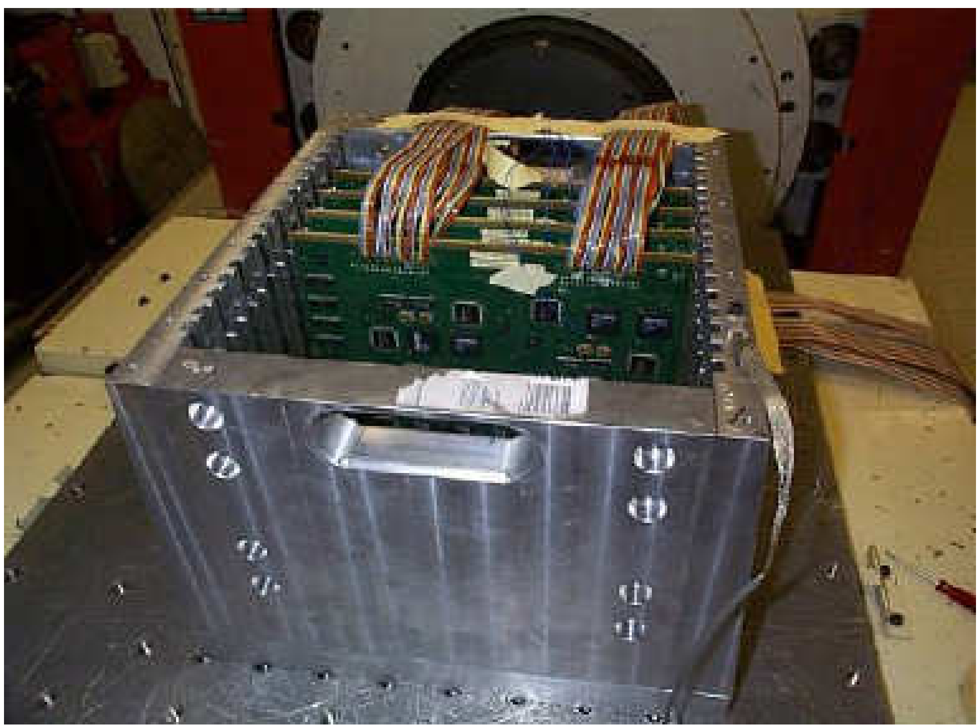
Three sufficient conditions resulting in unexpectedly high PDIP failures {cracked traces} on *lead-free* assemblies: **A+B+C = Failure**





Vibration Testing

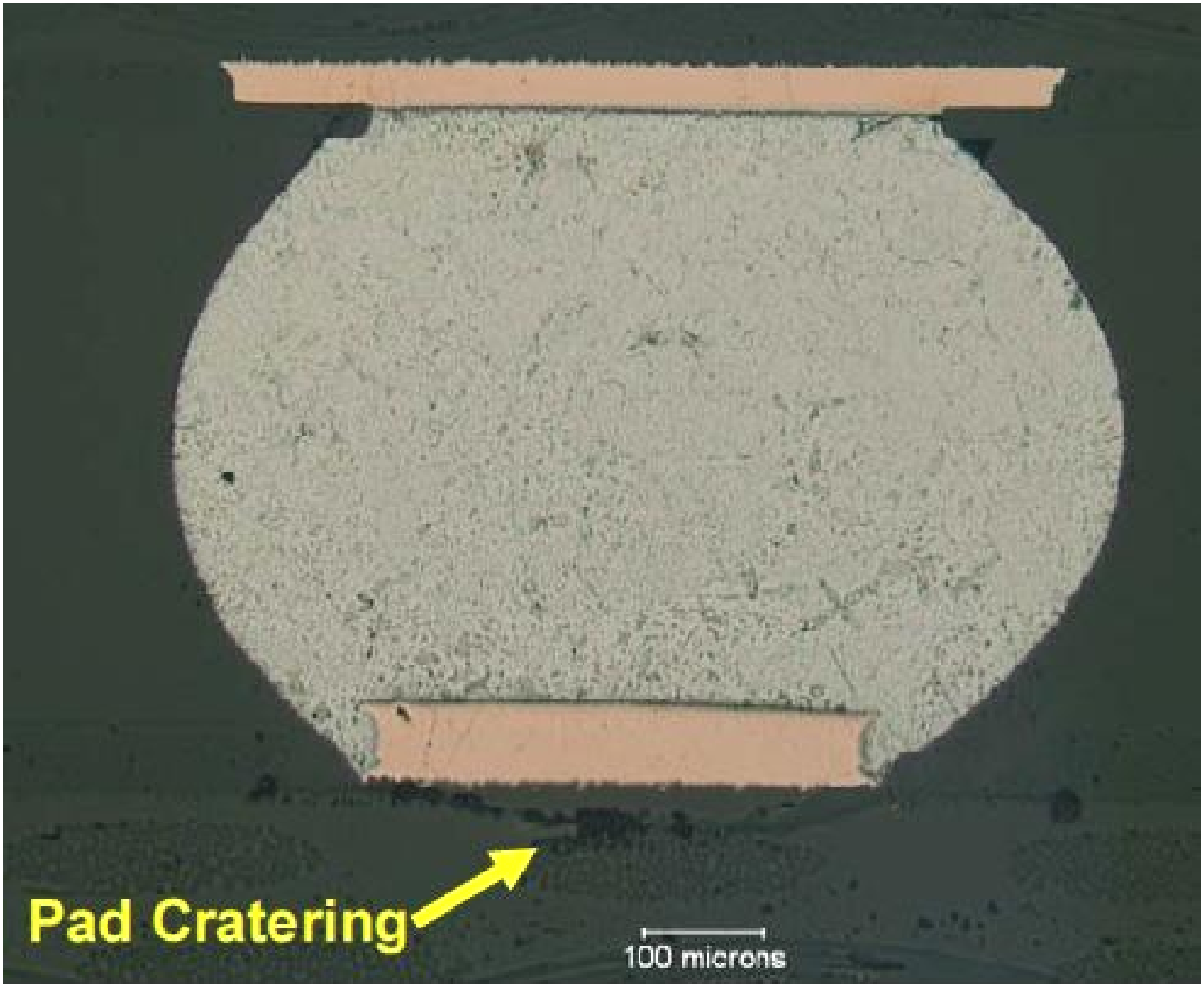
- Subject the test vehicles to 8.0 g_{rms} for one hour {Z-axis}.
- Then increase the Z-axis vibration level in 2.0 g_{rms} increments, shaking for one hour per step until the 20.0 g_{rms} level is completed.
- Then subject the test vehicles to a final one hour of vibration at 28.0 g_{rms} {Z-axis}.



Mechanical Shock Testing

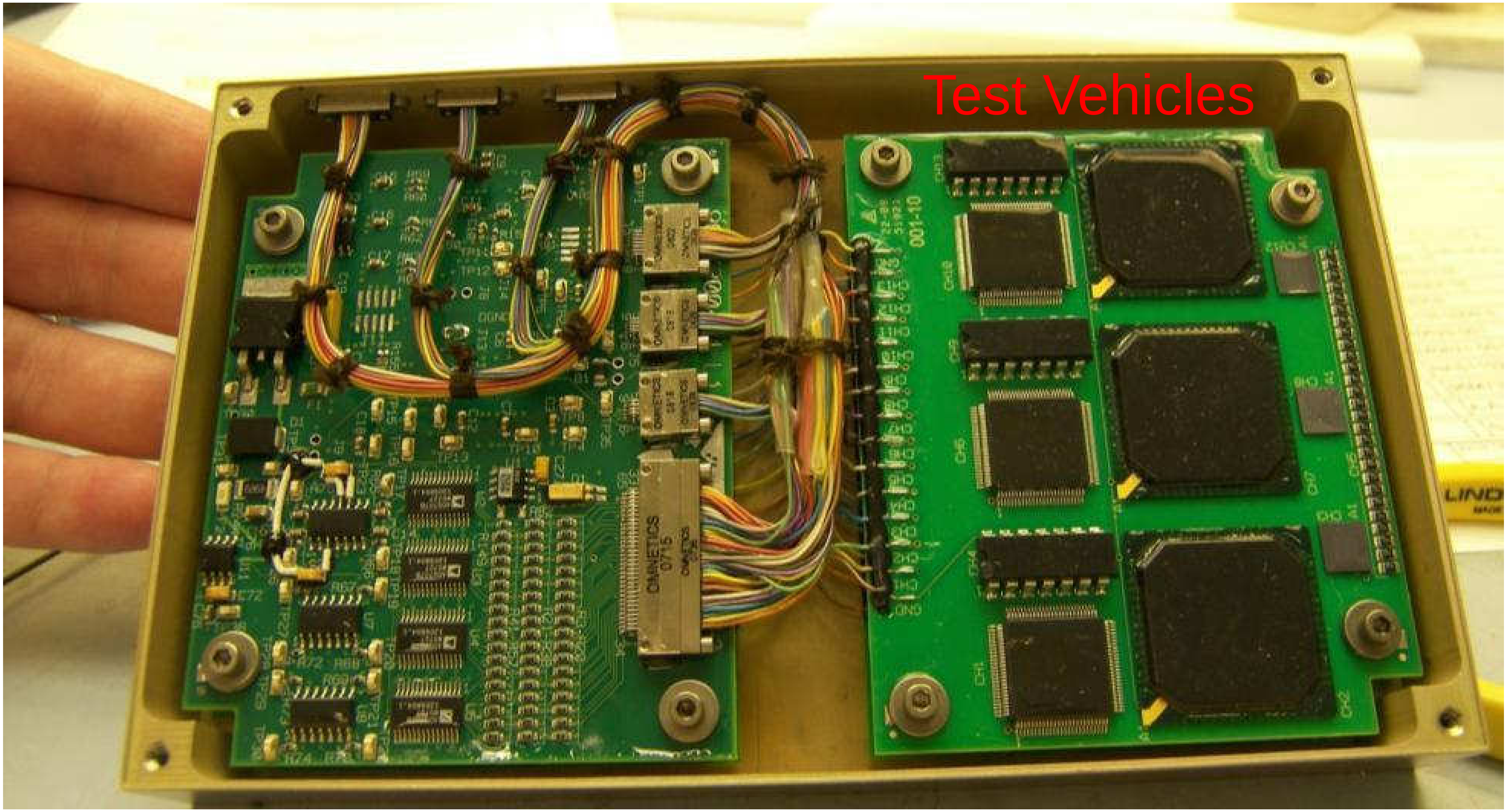
- Level 1: 100 shock pulses using a 20 G SRS
  - Functional Test for Flight Equipment; MIL-STD-810G, Method 516.6
- Level 2: 100 shock pulses using a 40 G SRS
  - Functional Test for Ground Equipment; MIL-STD-810G, Method 516.6
- Level 3: 100 shock pulses using a 75 G SRS
  - Crash Hazard Test for Ground Equipment; MILSTD-810G, Method 516.6
- Level 4: 100 shock pulses using a 100 G SRS
- Level 5: 100 shock pulses using a 200 G SRS
- Level 6: 400 shock pulses using a 300 G SRS

Mechanical Shock Testing



Lead-free Technology Experiment in Space Environment (LTESE)

- LTESE operated for about 17 months on the International Space Station



Lead-free Technology Experiment in Space Environment (LTESE)

- For the LF boards, there may be signs of tin whisker growth on the PDIPs {@ 1000X}
- For the mixed solder boards, some tin whiskers have been observed on the PDIPs {@ 1000X}
  - The cards are conformal coated {Solithane 113-300}
  - The whiskers do not exit the coating
  - These are on the knees of PDIPs on the flight mixed solder board {SnPb board with Pb-free parts using SnPb solder}.
  - The whisker on the CH4-Lead 6 is 18 µm long.