Implementing Pb-Free Assembly at Your Factory

by
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Acknowledgement

- **Vahid Goudarzi and his Motorola team**
  - For the work in this successful effort
  - For some of the figures and slides

Outline

- **Why Pb-Free?: We will not cover**
- **This Overview will be of a Successful Implementation at Motorola, Plantation, Florida, USA**
- **The Alloy: SAC**
- **PWB Finishes**
- **Component Concerns**
- **Solder Paste and the Process**
- **Additional Concerns for Large Boards**

Motorola Plantation

- **A 3 year development effort**
  - Cost: $1million (US)
  - Production started 2001
  - >> 1 million cell phones assembled world-wide
- **Contact:**
  - Vahid Goudarzi: EVG001@motorola.com
  - Motorola has been generous in sharing their results

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The Alloy Choice: SAC

- **Work by NEMI , JEITA , IDEALS , NCMS and materials suppliers support SAC**
- **NEMI Criteria:**
  1. No Bismuth: Concern with SnPbBi eutectic at 96°C
  2. T_m=217°C with <3°C Δ with common alloys
  3. Only 3 elements
  4. Less patent concerns
  5. Equal or better reliability than SnPb eutectic

The SAC Choice

- $SnAg_{3.9}Cu_{0.6}$ (+/0.2% for Ag and/or Cu)
- NEMI: No statistically different process or reliability performance within this range

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PWB Finishes

- A requirement should be that your process work well with all standard Pb-free finishes
- Motorola chose OSP
- MacDermid recommends Immersion Ag
  - BPatel@macdermid.com for finish details

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Component Concerns

- Higher Reflow Temperatures
  - Motorola targets 235°C peak to minimize concerns
  - TI has developed many packages for 260°C
  - 260°C may be needed for larger boards
- Lead Finishes
  - Motorola: Process must work with common Pb-free lead finishes
  - TI: NiPdAu to avoid tin whisker and shelf life issues, NiPdAU has no backward compatibility concerns
- TI Contact: James Huckabee: HUCK@ti.com

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Motorola's Process Criteria

- Paste must have good response to pause, tack, slump and other printing metrics
- The process/paste must show good coalescence and solder joint quality in a broad reflow process window
- The reliability of the finished product must be as good or better than the standard Pb solder
- The process must be simple and robust so that it can be transferred to other locations world wide

Paste Evaluation/Manufacturing Process Development

- Screen Printing Evaluation
- Reflow Profile Development
- Tackiness Measurement
- Surface Insulation Resistance (SIR) Evaluation

Pb-free Solder Paste Evaluation

Paste evaluation & selection strategy:
Work with 8 preferred paste suppliers to develop a lead-free solder paste that meets Motorola's manufacturing quality & product reliability requirements

The Finalists:

		Flux Vehicles		
		Phase # 1	Phase # 2	Phase # 3
Paste Suppliers	A	A1	A2	A3
	B	B1	B2	B3
	C	C1	C2	

Lead-free solder paste suppliers & materials

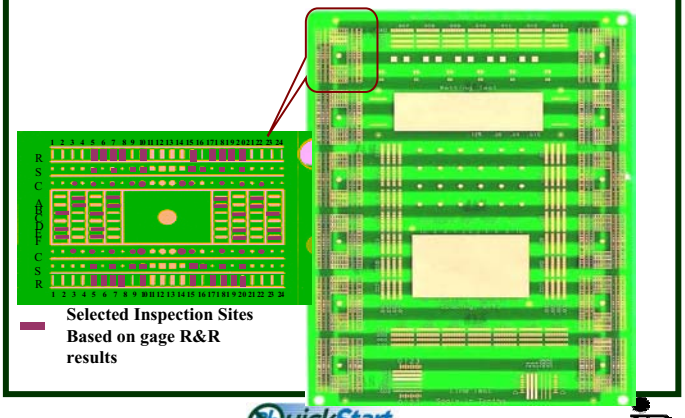
These studies were completed using Sn/Ag/Cu, Entek finish boards, & air atmosphere

Stencil Printing Evaluation

- **Objective: To ensure Pb-free paste performs consistently as a function of time**
- **Variables:**
  - Abandon time @ t=0, t=1, & t=4 hours
  - Solder paste (A1, B1, C1, A2, B2, C2, A3, B3)
- **Output:**
  - Volume measurement using laser system
  - Visually inspect for smearing and selected apertures for clogs

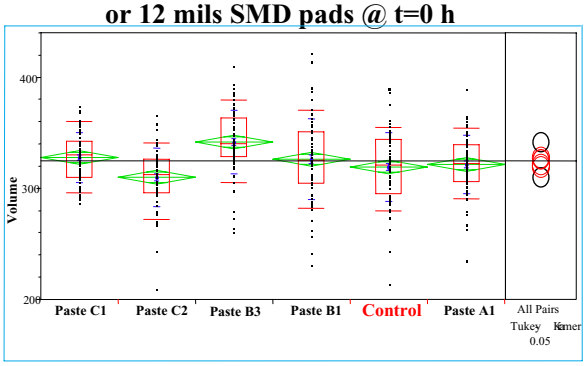
Optimum Print Speed, Squeegee Pressure, & Snap Off was set per paste supplier recommendation and validated

OSP Finish Test Vehicle for Paste Evaluation



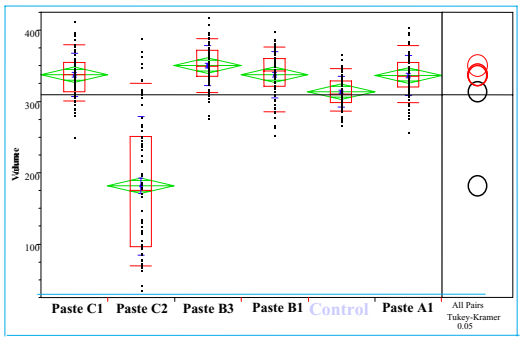
Selected Inspection Sites Based on gage R&R results

Solder Paste Volumetric Measurement or 12 mils SMD pads @ t=0 h



Pb-free Solder pastes performed well @ abandon time = 0h

Solder Paste Volumetric Measurement for 12 mils SMD pads @ t=1 h



Paste C2 failed @ abandon time=1h

Reflow Profile Development

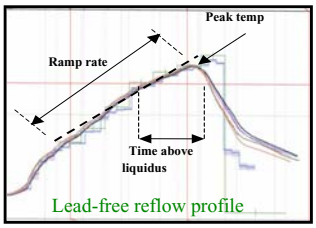
- **Objective: To determine reflow process window & identify a Pb- free paste which requires MINIMUM peak temp.**
- **Variables:**
  - Peak temperature
  - Time above liquidus
  - Solder Paste (A1, B1, C1, A2, B2, C2, A3, B3)
- **Output:**
  - Coalescent performance
  - Solder joint quality

Reflow Profile Matrix

Pb-free 2X3 Full Factorial Reflow DOE

- Minimize peak temp. to reduce thermal stress on Components
- Interaction between peak temp. & time above liquidus

Peak Temperature \ Time Above Liquidus	60Sec.	70Sec.	80Sec.
229C	P1	P4	P7
237C	P2	P5	P8
245C	P3	P6	P9

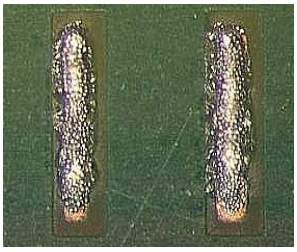


Selected paste MUST perform equally well @ P1 through P9 in air atmosphere

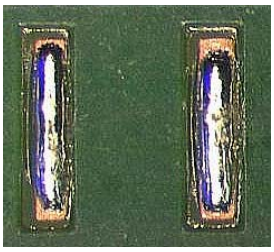
Reflow Profile Development Cont.

Inspection criterion:

Coalescent performance @ P1,P2, P3, P4, P5, P6, P7, P8 &P9



Poor Coalescent



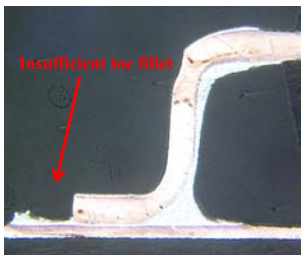
Good Coalescent

Poor coalescent is attributed to powder oxidation during reflow process in air atmosphere

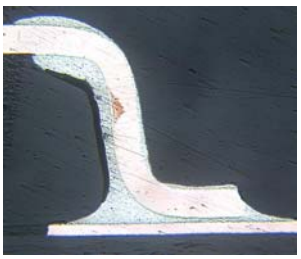
Reflow Profile Development Cont.

Inspection criterion:

Wetting performance @ P1,P2, P3, P4, P5, P6, P7, P8 &P9



Poor Solder Joint



Good Solder Joint

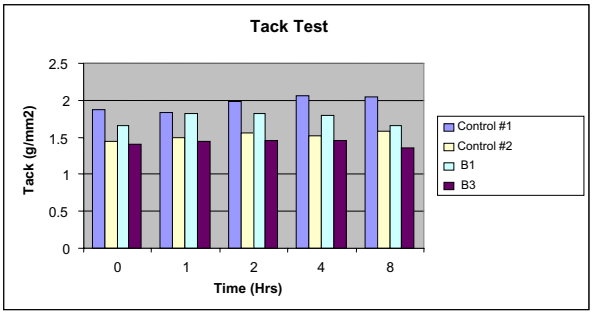
Insufficient toe fillet results in field reliability issues

Flux Tackiness Measurement

- **Objective: To ensure flux provides sufficient tackiness to hold components in place during manufacturing processes**
- **Variables:**
  - Paste life @ t=0;t=1h t=2h; t=4h; t=8h
  - Pb-free solder pastes
- **Output:**
  - IPC-TM- 650 Test Procedure: Measure the force required to Separate a 5mm diameter probe from paste
  - Shake Test -Automated vision inspection after placement

Flux Tackiness Measurement Cont.

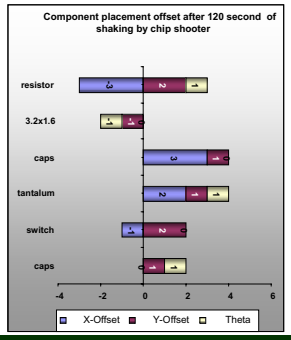
IPC650 Tack Test - Tack test evaluation result



Flux Tackiness Measurement Cont.

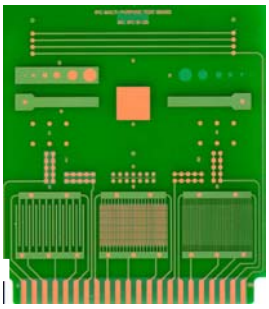
To ensure flux provides sufficient tackiness to hold components in place during assembly process

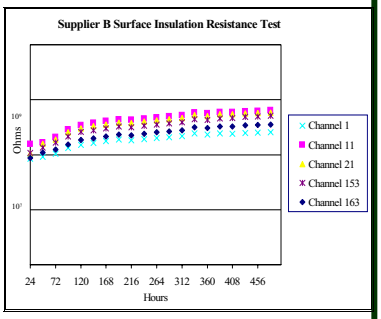
1) Populated PCBs after 0, 4, and 8 hours
2) Image components to determine X, Y, and Theta offsets.
3) Place PCBs on XY table of Chip Shooter & shake PCBs for 120 Sec.
4) Image components to determine X, Y, and Theta offsets
5) Determine delta for before & after shake process



Surface Insulation Resistance

Motorola SIR Test Boards = B25 Test Board + Solder mask





SIR requirements is minimum of 10 ^{8} Ohms

Paste Final Evaluation Results

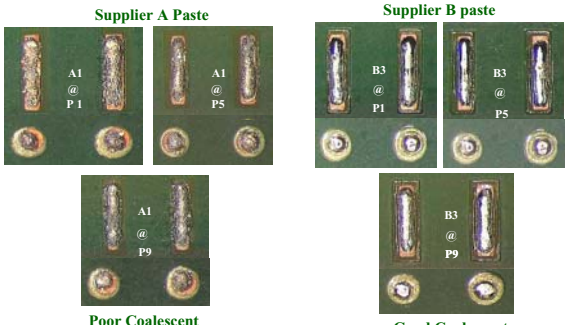
		Phase 1			Phase 2			Phase 3	
		Paste B1	Paste A1	Paste C1	Paste B2	Paste A2	Paste C2	Paste B3	Paste A3
Printing Paste	Visual Inspection	✓	✓	✓	✓	✓	✓	✓	✓
	Volumetric data	✓	✓	✓	✗	NT	NT	✓	NT
Reflow	P1,P5,P9	✓	✗	✗	✓	✗	✗	✓	✗
	P1,P2,P3,P4,P5, P6,P7,P8,&P9	✓	✗	✗	✓	✗	✗	✓	✗
Tackiness	Instron IPC650	✓	NT	NT	NT	NT	NT	✓	NT
	Shake Test	✓	✓	NT	✓	NT	NT	✓	NT
Quality	Solder Joint	✓	NT	NT	✓	NT	NT	✓	NT
	ALT	✓	NT	NT	NT	NT	NT	✓	NT
SIR	J-STD B25	✓	✓	✓	✓	✓	NT	✓	NT
	Motorola	✗	NT	NT	✓	NT	NT	✓	NT

✓ Passed ✗ Failed NT Not tested

Paste B3 met all requirements

Paste Final Evaluation Results Cont.

Solder Coalescent Comparison @ P1, P5, & P9



Paste A1 does not fully coalesce and result in grainy joint due to powder oxidation in air atmosphere

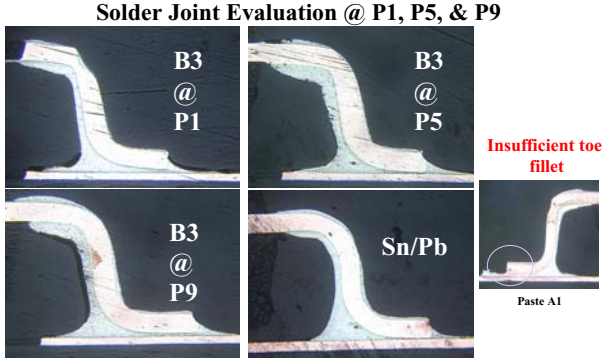
Paste Final Evaluation Results Cont.

Solder Joint Evaluation @ P1, P5, & P9

No significant difference in solder joint fillet @ P1, P5, & P9 using B3 solder paste

Paste Final Evaluation Results Cont.

Solder Joint Evaluation @ P1, P5, & P9



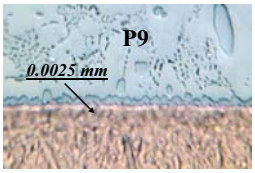
Insufficient toe fillet

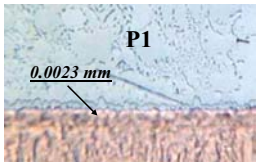
Paste A1

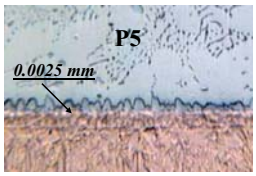
No significant difference in solder joint fillet @ P1, P5, & P9 using B3 solder paste

Paste Final Evaluation Results Cont.

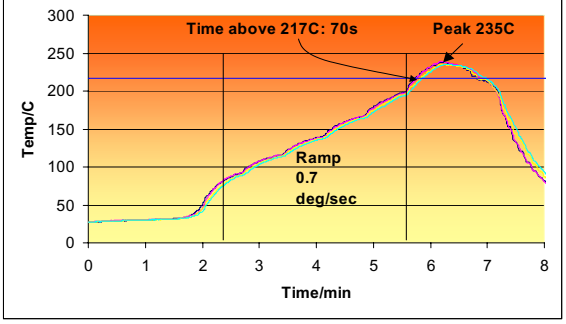
Intermetallic formation







Recommended Profile for B3



Peak Temp. = 235 C +/- 5C; Time Above Liquidus = 70Sec +/ 10Sec

Reliability Evaluation

Product Level & Solder Joint Reliability Evaluation

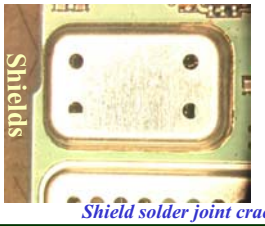
- Drop Test
- Shear Test
- Liquid-to-Liquid Thermal Shock
- ALT for different Products

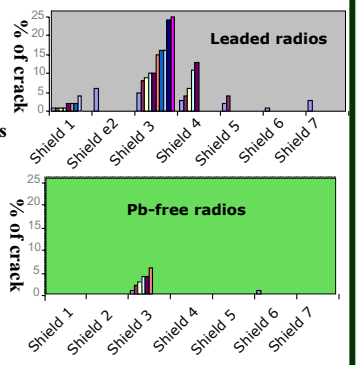
Pb free solder joints MUST perform equal or better than leaded solder joints

Reliability Evaluation Cont.

Drop Test

1) Dropping products from 5 feet
2) Vert. & horiz.vibration for 2 hrs
3) Thermal shock for 48 hrs
4) Repeated step 1 thru. 3 X times
5) Measure % joint cracks on shields



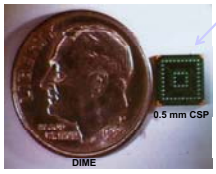


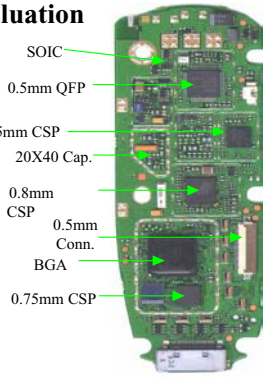
Shield solder joint cracking is significantly reduced using B3

Reliability Evaluation Cont.

Solder Joint Reliability Evaluation Test Vehicle

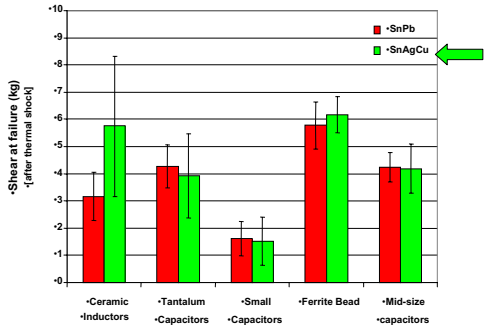
- 6X6 mm Package size
- 0.5 mm pitch partial array
- 0.3 mm solder balls size





Reliability Evaluation Cont.

Shear Test



No significant difference in shear force after LLTS.

Reliability Evaluation Cont.

Liquid-to-Liquid thermal shock evaluation (-55 °C to +125 °C)

Variables:

- Solder Paste (Paste B3 & Pb Paste)
- Component Type (0402, 0603, 0805, BGAs, CSPs, VCO, Transformer)

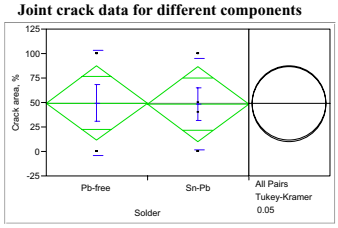
Output:

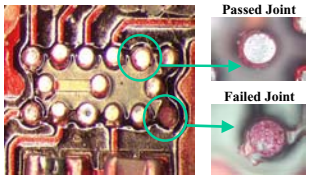
- Electrical test at every 75 cycles for 450 cycles
- Red dye analysis at 150, 300, and 450 cycles

Reliability Evaluation Cont.

Liquid-to-Liquid thermal shock results after 450 cycles

Joint crack data for different components





Red dye evaluation result

No significant difference in cracked area in leaded and Pb-free joints

Products Built with Pb-free Paste

Products built with Pb-free solder paste and passed ALT

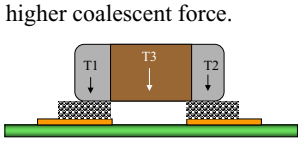
Manufacturing Issues

- Tombstone Failures
- Air Voids on CSPs
- Logistics: Have a Plan to Avoid mixing SnPb and Pb-free Assembly

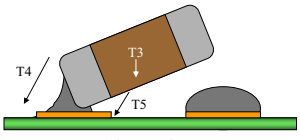
Manufacturing Issues Cont.

20X40 Tombstone Failures

Lead-free Solder paste is more prone to tombstone failures due to higher coalescent force.



Before Reflow



After Reflow

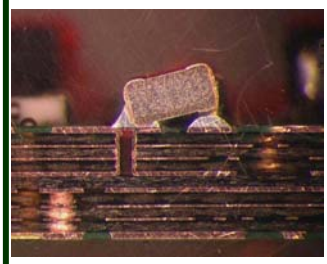
T1 & T2 : Tack Force
T3 : Weight
T4 : Surface Tension (outside)
T5 : Surface Tension (underneath)

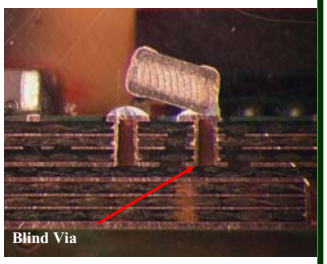
T4 is significantly higher using lead-free solder paste

Manufacturing Issues Cont.

20X40 Tombstone Failures

Tombstone failures are attributed to lead-free solder paste & blind vias





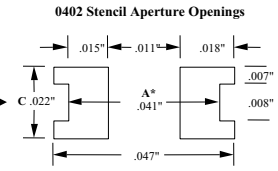
Pads without blind vias did NOT show tombstone failures

Manufacturing Issues Cont.

20X40 Pad Design for Conventional PCB

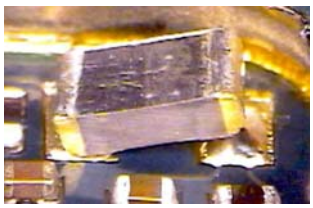
Evaluated Circle, ½ Circle, Rectangular (vertical & horizontal), Oblong, square stencil, etc.

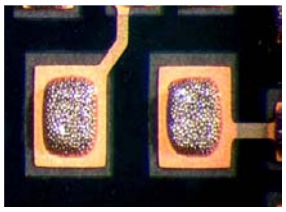
Stencil design to minimize tombstone failures on pads with blind vias



Manufacturing Issues Cont.

Tombstone / floating Failures



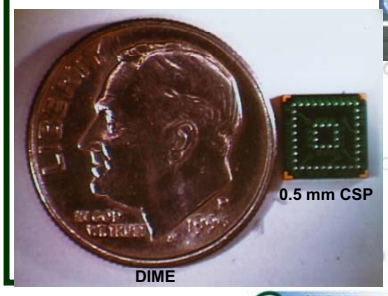


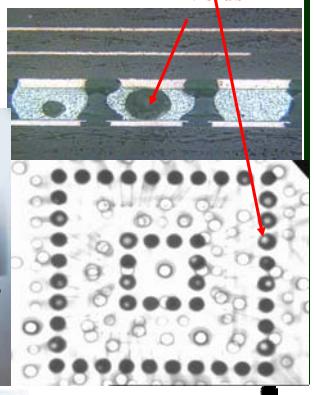
Paste volume was reduced to eliminate tombstone failures on large discrete inductors

Manufacturing Issues Cont.

Air voids on CSPs

- **6X6 mm Package size**
- **0.5 mm pitch partial array**
- **0.3 mm solder balls size**

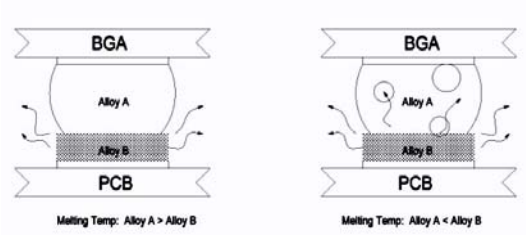




Manufacturing Issues Cont.

Voids Mechanism in CSPs

1) Solder bump oxidation
2) Flux out gassing



Manufacturing Issues Cont.

Air voids on CSPs

BGA/CSPs are more prone to voids mainly due to leaded bumps on package & increased oxidation of powder due to higher reflow temp.

Variables:
- Ramp Rate
- Solder Paste

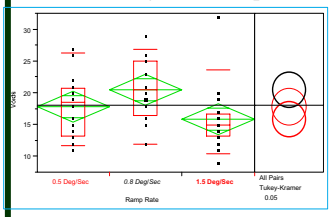
Outputs:
- Number of voids
- Void size

Ramp Rate (Deg./Sec.)	Solder Pastes: Paste B3	Paste #15	Paste #16
0.5	CSPs	CSPs	CSPs
0.8	CSPs	CSPs	CSPs
1.5	CSPs	CSPs	CSPs

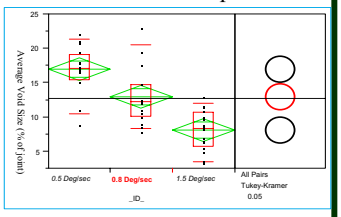
Manufacturing Issues Cont.

Air Voids in CSPs joints

Void Quantity VS. Ramp Rate



Void Size VS. Ramp Rate

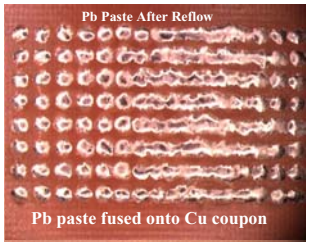


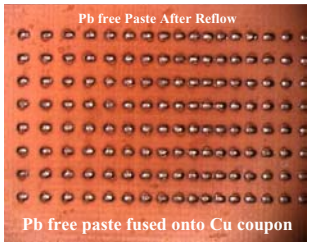
- *Quantity of voids are not significantly affected by ramp rate*
- *B3 shows significant reduction in void size as ramp rate increases*

Pb-free Joint&Component Appearance

4) Joint & Component Appearance

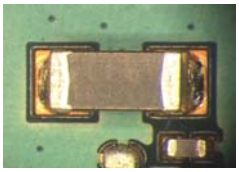
Coalescent Performance Comparison

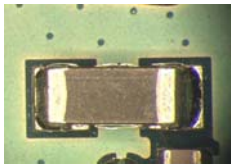


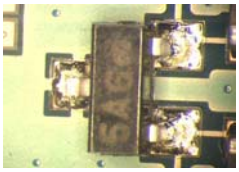


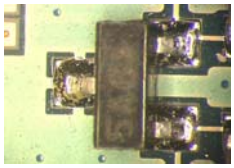
Pb-free Paste has a significantly higher Coalescent force

Solder Joint Comparison







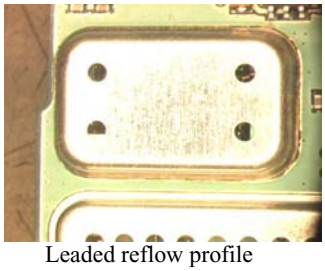


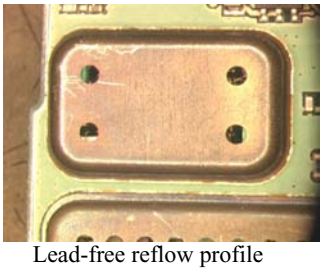
PasteB3 **Control(Pb)**

Pb-free Joint &Component Appearance Cont.

Shield Discoloration

SnO & SnO2 is formed after lead-free reflow process.





Leaded reflow profile Lead-free reflow profile

Oxidation does not affect electrical performance

Motorola Pb-Free Implementation Summary

- ✓ **Solder Paste Selection** - Evaluated 19 different Pb-free solder pastes and selected B3 (Indium SMQ230 lead-free solder paste) based on manufacturing and product level reliability requirements.
- ✓ **Manufacturing processes -** Reflow profile, screen printing operation, tackiness evaluation, etc. completed
- ✓ **Reliability Evaluation -** Pb-free solder joint reliability evaluation has shown equal or better performance compared to current materials
- ✓ **Components** - 100% of the components Pb-free qualified
- ✓ **Electrical & Mechanical** - 100% completed with NO issues
- ✓ **Quality -** No manufacturing/product quality issues; DPHU goal were met

Motorola Pb-Free Summary

- ***Production since 09/04/01***
- ***Many site implementation***
- ***More than 1M cell phones have been shipped to the field***
- ***No field reliability issues have been encountered***

Topics Not Discussed

- **Rework: Gold Goudarzi**
  - EGG011@email.mot.com
- **Large Board Assembly: Eddie Hernandez**
  - eddie.Hernandez@hp.com
  - Eddie will be presenting this work at this conference, Wed Oct 22
- **Wave Soldering: Denis Barbini**
  - dbarbini@us.vitronics-soltec.com

Appendix: Process Optimization Plan

- **Assess Yourself**
  - Crucial with Pb-free
- **Use the Right Tools**
  - DOE
  - SPC
- **Indium Process Software to Help**

Assessment Categories

- **DFM, Process and Equipment**
- **Materials Supply and Validation**
- **DOE, SPC, CIP**
- **Training and Failure Analysis**
- **Developed from pooled information from industry experts**

DFM, Process and Equipment

Ranking Key: 0 = strongly disagree or don't know , 3 = disagree, 5= neutral, 7 = agree, 10 = strongly agree

1	We have a documented and functioning DFM system that includes design ground rules (DGRs). Our entire organization is strongly committed to DFM. DFM is a way of life (this question counts 3 times):	10
2	Our DGRs are established by using designed experiments and statistical process control:	8
3	The process engineers know how to run all of the equipment:	3
4	The engineer(s) responsible for stencil printing knows how to design a stencil	9
5	The engineer(s) responsible for component placement knows how to balance and optimize the placement equipment. He assures that this operation is performed on all jobs:	9
6	The engineer in charge of the reflow process assures that the reflow profile matches the solder paste specification:	9
7	Our process engineers have a disciplined and proven strategy to improve productivity:	9
8	Our process engineers have a disciplined and proven strategy to improve quality:	9
9	Our process equipment is "qualified" with a test and evaluation procedure that is founded on DOE principles:	3
10	There is a process engineer or team of engineers responsible for implementing new processes and technology:	9
	Total Score out of 120	98

Ratings:
World Class = > 95
Above Average = 75 - 94
Average = 55 - 74
Below Average < 55

Your score places you as "World Class" in DFM, Process and Equipment for SMT assembly. Your clearly recognize the importance of these topics in your assembly processes. This score still offers some opprotunity for improvement. Look at your results on each question and develop an action plan for improvement if appropriate.

Materials Supply and Validation

Ranking Key: 0 = strongly disagree or don't know , 3 = disagree, 5= neutral, 7 = agree, 10 = strongly agree

1	We evaluate our solder pastes and/or materials with a systematic evaluation procedure, such as "The 12 Board Paste Evaluator" (shown below) or DOE to assure its performance (this question counts 3 times):	0
2	My engineers have read and understand the solder paste and materials specs and assure they match our use conditions:	8
3	The response to pause of my solder paste is adequate for my applications:	5
4	The cost of my solder paste and/or materials is the main criteria for its purchase:	3
5	The printed volume consistency of my solder paste is best of breed:	5
6	My materials supplier(s) understand(s) my process and business needs, we treat each other like partners:	4
7	Few, if any end of line defects can be traced to inadequacies of my solder paste and/or materials:	4
8	The type (i.e. 2, 3, 4, 5) of the solder paste we use matches the application requirement:	4
9	Our organization has a systematic method to assure that the materials/components for future jobs are being prepared while current jobs are being run:	6
10	Our organization has a systematic method to assure that we have an uninterrupted supply of materials from our vendors:	6
	Total Score out of 120	49

Ratings:
World Class = > 95
Above Average = 75 - 94
Average = 55 - 74
Below Average < 55

Your score places you below average among users of SMT materials. This position offers overwhelming opportunities for improvement. Look at your results on each question and develop an action plan for improvement. Your organization has an urgent need to recognize that evaluating your solder pastes and materials is a most important activity.

DOE, SPC, CIP

Ranking Key: 0 = strongly disagree or don't know , 3 = disagree, 5= neutral, 7 = agree, 10 = strongly agree

1	We have a continuous improvement plan that is effective, uses metrics, and is recognized as valuable by the entire organization (this question counts 3 times):	3
2	We measure our process uptime:	8
3	We measure our unscheduled downtime:	2
4	We measure our line efficiency:	2
5	We measure our work in process time:	5
6	We know our process's Cp and Cpk:	9
7	We have a statistical process control program and use the resulting data effectively to monitor and improve our processes:	9
8	Our process engineers use designed experiments to optimize our processes and evaluate equipment and materials:	9
9	Quality is everyone's job:	8
10	Productivity is everyone's job:	8
	Total Score out of 120	69

Ratings:
World Class = > 95
Above Average = 75 - 94
Average = 55 - 74
Below Average < 55

Your score places you as average in DOE, SPC and CIP for SMT assembly. This position offers significant opportunities for improvement. Look at your results on each question and develop an action plan for improvement. Having an effective CIP program is vital for success.

Training and Failure Analysis

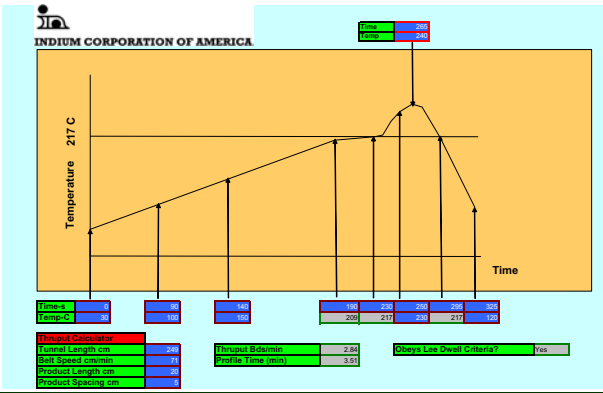
Ranking Key: 0 = strongly disagree or don't know , 3 = disagree, 5= neutral, 7 = agree, 10 = strongly agree

1	Our organization has a sophisticated training program for all levels of our staff (this question counts 3 times):	9
2	Our engineers understand the difference between common cause and special cause failures and use this knowledge in process troubleshooting:	8
3	Our engineers use sophisticated modeling tools, like StencilCoach, Reflow Coach and LineBalancer to help them model processes and perform "what if" analysis:	5
4	Management uses costing tools like ProfitPro to perform financial "what if" analysis, before making financial investments in equipment etc:	3
5	Our operators cannot change the process equipment's operating parameters:	8
6	Our engineers know and use analytical problem solving and brainstorming techniques to perform failure analysis:	4
7	There is a process line escalation policy that is understand by all (e.g. if the line is down and remains down this information gets escalated in a documented fashion):	4
8	Our process engineer's yearly performance review is related to process improvement goals:	4
9	We can perform failure analysis or vend this task out:	6
10	Our staff has all ot the tools necessary to perform their jobs:	6
	Total Score out of 120	75

Ratings:
World Class = > 95
Above Average = 75 - 94
Average = 55 - 74
Below Average < 55

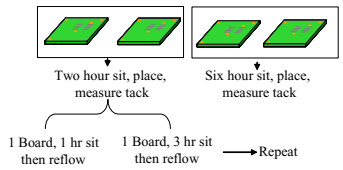
Your score places you as above average in Training and Failure Analysis for SMT assembly. This score still offers considerable opportunity for improvement. Look at your results on each question and develop an action plan for improvement, if appropriate.

ReflowCoach™



The Twelve Board Paste Evaluator

1. **Start with enough paste for 12 prints**
2. **Print 4 boards (no kneading)**



Metrics to Measure:
- Print Volume
- Print Definition
- Volume and Definition after Idle
- Release from Aperture
- Squeegee Hang up
- Tack
- Solder Joint Quality

For Final Candidates
- Coalescence
- Reflow Window
- J Standards

3. **Pause one hour, no kneading, print 4 more boards, repeat tests in 2**
4. **Pause one hour, no kneading, print 4 more boards, repeat tests in 2**

But No Matter What You do Have a CIP?

- **Assess yourself**
- **Establish/Measure Metrics**
  - Paste Volume
  - Component Placement Metrics
  - Pareto Defects
- **Develop Action Plan**
- **Fix the Problems**