Assembly of Large PWBs in a RoHS Environment

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Introduction

As early as 2001, leading cellular phone manufacturers had established stable assembly processes that were RoHS compliant for their cellular phone products. Since this time, the products manufactured on these lines have demonstrated equal or better quality and reliability as compared to cellular phones assembled with tin-lead solder and non-RoHS compliant components. This success may have created the belief that there are few issues remaining in RoHS compliant assembly. This belief is far from the truth. Organizations that need to assemble a wide range of large, thick printed wiring boards (PWBs) continue to have considerable process challenges. These difficulties – combined with the need to assemble RoHS 5 (tin-lead solder paste and components with tin-lead finished leads, the remaining hardware being RoHS compliant), RoHS 5.5 (RoHS 5 with BGAs that have SAC or SACX solder balls) and RoHS 6 (fully compliant RoHS assembly) in one facility – create not only assembly technical challenges, but considerable material handling and logistics issues.

This paper is a review of the work done at Jabil in Billerica, Mass., to address these challenges. An overview of the process development work in stencil printing, component placement and reflow soldering that was required to develop optimized assembly processes for PWBs with dimensions exceeding 56 cm and thicknesses approaching 0.3 cm will be discussed. The methods developed to handle the logistics issues of having RoHS 5, RoHS 5.5 and RoHS 6 assembly in one facility will also be presented.

The paper will conclude with a review of several of the products currently being assembled with these processes and logistics.

The Challenges of Electronic Assembly in a Post RoHS World

The advent of the EU's restriction of hazardous substance (RoHS) on 1 July 2006 has magnified the complexity of assembling electronics products significantly. Not only do assemblers have to be concerned with managing the issues of RoHS, the EU has created numerous exemptions for telecommunications, medical device and controls electronics that create the need to assemble varying levels of RoHS compliant products. These multiple types of products are often assembled in one facility, creating numerous logistics and assembly process challenges. For an Electronic Manufacturing Services provider (EMS) an additional challenge exists in working with our Original Equipment Manufacturer or OEM customers, in this environment to develop a complete business process to deliver world-class products, on time, at a competitive cost.

In light of this changing environment set up the following strategy to succeed with our customers.

Begin by Working with the Customer

We found that the RoHS requirements made it more important than ever to work with our customers as a team. In light of this approach, we found it vital to assure that we and our current and prospective customers understood the issues relating to RoHS compliancy, end product reliability, materials management, design for manufacturability, process optimization, design and manufacture for testability and repair, and production scale-up issues from prototype to full volume production.

To manage this model successfully we established a "RoHS Account Setup and Management Initiative" internally. To assure the success of this approach we needed the commitment of both our business management (BM) and technical management (TM) teams. This model consisted of four major foundational blocks:

1. Customer "development" with a goal to bring the prospective Customer up to speed Re: the latest RoHS related issues including technical presentations, training sessions, etc. which is absolutely vital for success of the following steps
2. Establishing and analyzing deliverables necessary for product assembling
3. Customer account multi-level technical and business analysis
4. Setting up and executing of required sub-projects to assure customer special requirements are met. These sub-projects could include:
    a. Technical tasks
    b. Materials management

c. Strategic partnerships

On the operational side of our business, we assured that the following concerns were addressed and monitored by:

- Communication between ourselves and our customer
- Communication between BM and those executing the tasks to deliver the end product
- Establishing a "watchdog" function to assure all production functions and RoHS compliance fails were cataloged and analyzed by root cause analysis
- Establishing and executing an effective data management system
- Color coding between RoHS 5, RoHS 5.5 and RoHS 6
- Training at all levels to assure everyone understands the RoHS compliancy issues and how they affect us.

Our concept in working most effectively with our customers is to share responsibilities in a way that maximizes effectiveness and minimizes cost. In light of this approach, the customer typically provides the design, structured so that it supports their compliant approved vendor list (AVL) for most components and hardware. The EMS is then responsible for all other material, often referred to as MRO (maintenance, repair, and operating) materials used for assembly purposes. This split of the materials establishes a sound foundation for documentation to support traceability and compliancy analysis. Jabil also manages the data related to production runs when using shared production facilities between different RoHS product levels, changeover checklists, audit data, and solder pot content analysis for all RoHS 5 and RoHS 6 systems and third party services provided for customer products. Third party services are often overlooked during the setup of a RoHS compliance system and can ultimately contribute to compliance or even product reliability failures from such processes as outsourced rework.

After establishing the system described above, we performed an audit and from the results, set up appropriate training modules both internally and for our customers. This training assured that we and our customers approached RoHS compliant assembly from the same baseline.

Component Challenges

One of the greatest RoHS challenges is the constant transition of components through engineering change orders (ECO), materials change orders (MCO) and "deviations." Any of these changes can alter the status of a component from RoHS 6 down to RoHS 5. These changes, which are often beyond our control, can require engineering evaluations and dramatically affect the assembly "process window." Internally we use color identification, green for RoHS 6 and yellow for RoHS 5. This color-coding is applied to all aspects of the process: components, equipment, procedures, materials and assembly space. This color-coding strategy is rigorously adhered to avoid any "cross contamination" between the RoHS levels. Date codes are also set and managed for every relevant material.

The Process

Every dedicated piece of RoHS 6 equipment, such as stencil printers, placement equipment reflow ovens, wave soldering machines, benches, racks, tables, etc has a green label. The equipment is also located in designated areas that are marked with green signs. Paperless documentation carries the same similar green logos and is linked to the latest waivers, deviations, etc. All relevant materials are located in designated areas and marked with the same green signs. Wave soldering bars have unique shapes, rectangular for RoHS 5, triangular for RoHS 6.

One of the critical issues in RoHS 6 assembly is the reflow process window. RoHS 6 assembly uses SAC solder (typically 96.5% tin, 3.0% silver, 0.5% copper) which melts at around 217-222^{o}C, about 35^{o}C higher than tin-lead's 183^{o}C. This higher melting temperature for SAC solder results in the reflow process window for RoHS 6 being much tighter than for tin-lead (RoHS 5) assembly. See Figure 1. This situation exists because many components are not designed to be exposed to temperatures above 245^{o}C to 260^{o}C or so. These circumstances result in some RoHS 6 reflow process windows having a minimum temperature of 235^{o}C and a maximum 245^{o}C, where the former is related to the minimum soldering temperature and the latter to maximum temperature at component. This 10^{o}C delta can be a challenge to control.

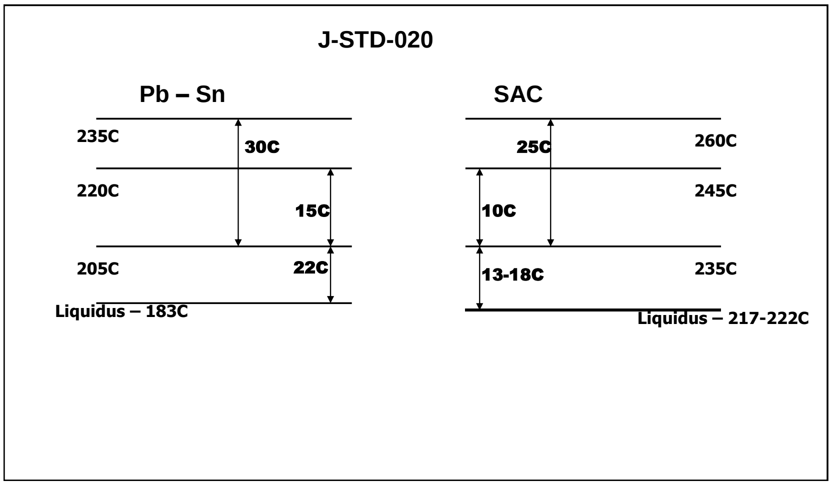

Figure 1. Reflow process window comparison between tin-lead (RoHS 5) and SAC RoHS 6 solder assembly.

The J-STD-020 standard recognizes that variations in the reflow process and other tolerances may slightly alter the process window in Figure 1. This process window is shown in Figure 2.

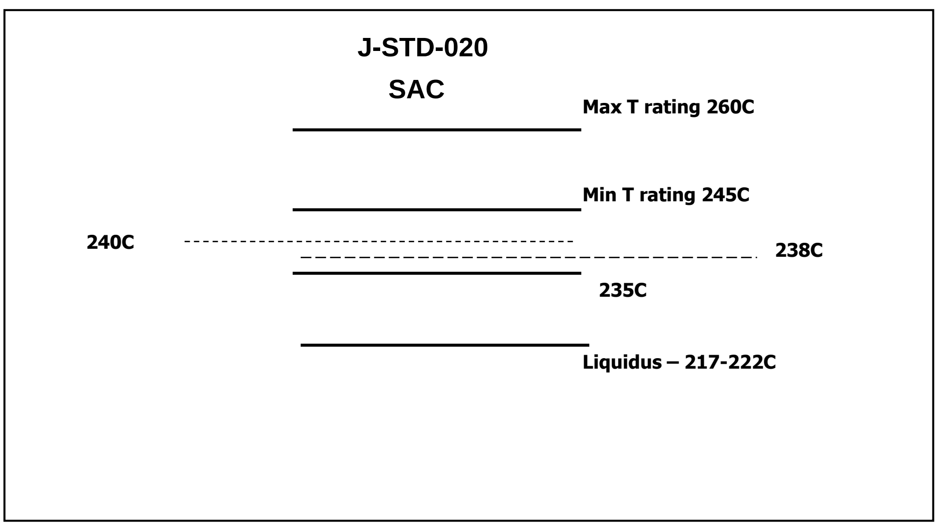

Figure 2. SAC process window modified to accept variations and tolerances.

The reflow process window challenge, in many cases, is that if the component manufacturer demands a maximum temperature of 240^{o}C (which per the latest version of J-STD-020 was brought up to 245^{o}C, but still is a concern on the production floor), the theoretical process window may be down to 5^{o}C. When considering process safety factors or assembling process variation, the same theoretical window could further be reduced to 2^{o}C. In addition to this challenging situation is the fact that the J-STD standard and the EIAJ standard do not necessarily agree.

All of these requirements make accurate oven profiling, monitoring and maintenance a must.
A similar analysis of RoHS 5.5 (RoHS 5 - tin-lead solder exempt product assembled with BGAs that have SAC / SACX solder balls) assembly stresses the need for accurate reflow profiling. RoHS 5.5 product must be reflowed at a minimum of

221^{o}C to assure complete melting of the SAC solder ball. (Actually it can be slightly below the melting point, but must be supported with reliability verification for every relevant case). Without the complete melting the resulting solder joint may have reliability issues including generally overlooked "tilted" large BGA where two corners may have a reasonable delta T.

Hence, one must set the oven at 224^{o}C to allow for normal process variations to assure the BGA balls melt. However, remembering that a RoHS 5.5 product is really a RoHS 5 product with a BGA with SAC solder balls, some of the components in the RoHS 5 classification may be rated at only 220 ^{o}C. See Figure 3.

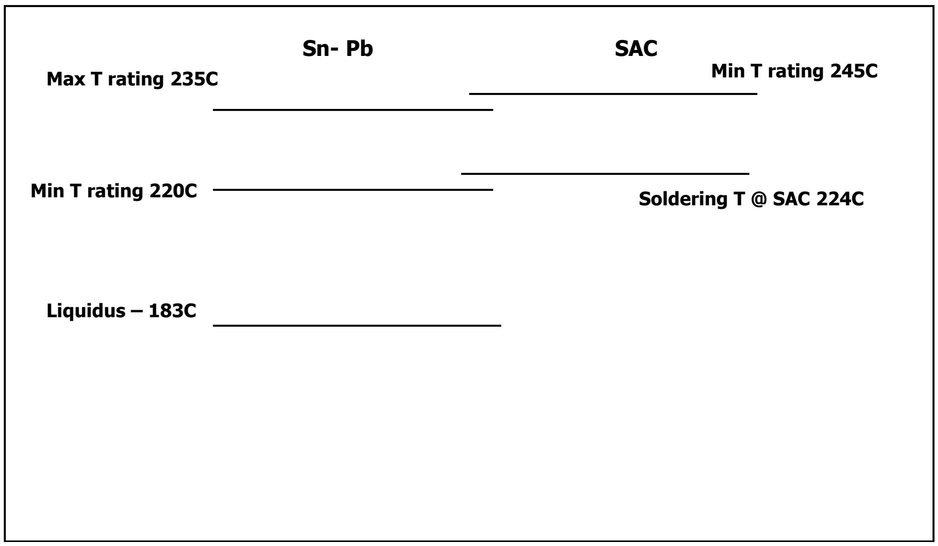

Figure 3. The temperature profile requirements for a RoHS 5.5 product.

In addition to the above reflow process window challenges, one must consider:

- Proprietary alloys such as SACX have even higher liquidus temperatures
- Some fine pitch components are exempt from RoHS 6 (i.e. their leads can contain tin-lead solder), hence the plastic body may be low-temperature rated, but these components are still assembled in a RoHS 6 environment (i.e. SAC solder paste used, because other components are not ROHS 6 exempt)
- High temperature Sn/Pb solder balls – also exempt from RoHS 6 – may need additional temperature activation to create reliable solder joint with SAC alloy
- Through hole devices may have their bodies exposed to much higher than expected temperatures when assembled with SAC solder

In summary, the reflow profile temperature assessment step is a "must" that can mitigate, but not rule out possible component failures induced by the higher temperatures at the given times above liquidus of RoHS 5.5 and RoHS 6 assembly. See Figure 4. For the greatest likelihood of assembly success, it is vital to work with the component suppliers on the AVL to assure that the components they provide will meet your RoHS 5.5 and RoHS 6 assembly needs.

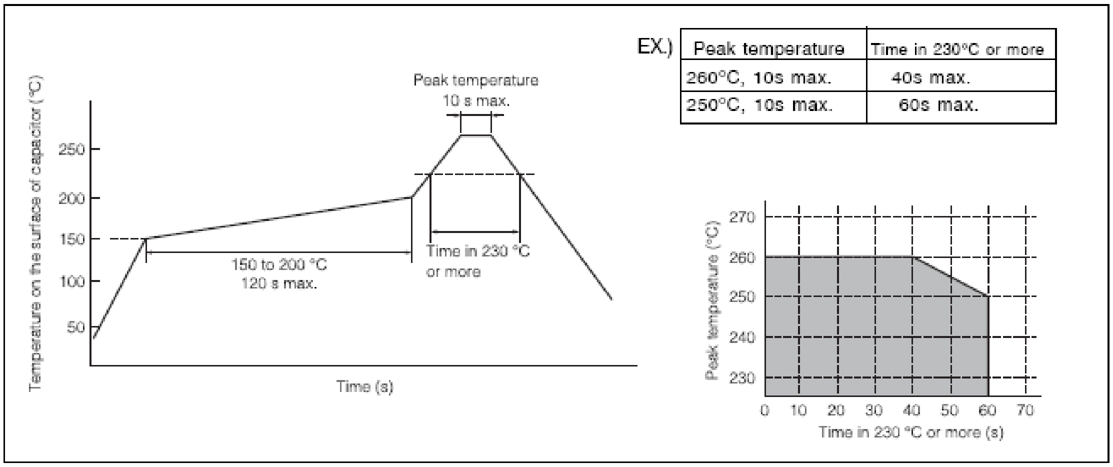

Figure 4. RoHS 6 component with maximum temperature limitations

Large PWB Challenges

In addition to the challenges mentioned so far, many PWBs for telecommunications and industrial products are very large, going beyond the evaluation procedures recommended by IPC-9850 and other similar standards. In such large PWBs (> 50 cm), the lack of dimensional stability and equipment tolerance control can result in difficulties in accurately stencil printing and placing components.

Because of these concerns, we performed experiments to assess the precision of our stencil printing and component placement operations. To evaluate the stencil printer's precision, two stationary cameras were installed on the printer, then PWB load and alignment was repeated 50 times to capture X and Y data distribution for two fiducials 53.3 cm apart. The tolerance was +/- 0.025 mm. The resulting C_p[i] data were:

$C_p X_1 = 8.28$
$C_p Y_1 = 2.23$
$C_p X_2 = 3.58$
$C_p Y_2 = 3.28$

These encouraging results enabled us to extend our printing capability limit up to a 75 cm PWB. The experimental setup is seen in Figure 5.

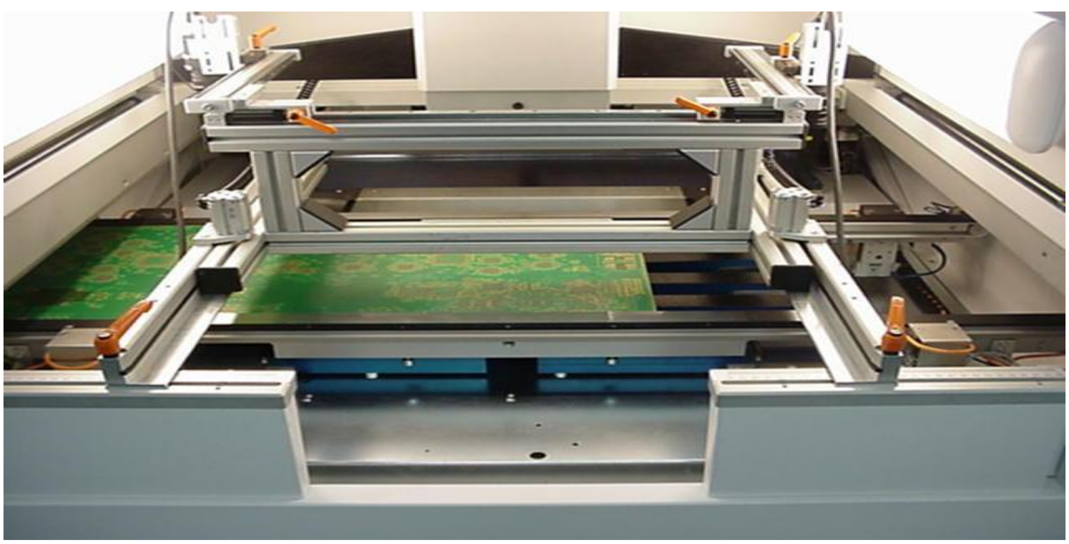

Figure 5. The experimental setup to determine stencil printing precision.

To assess placement capability a 16 board run was used for 0402 passive "chips" and a 100 pin QFP glass slugs. The slugs were placed on an aluminum board. Two drilled holes in the board were used as fiducials. This approach would be expected to produce poorer results than using a glass calibration substrate, which has 6 fiducials and has excellent tolerance control. Hence, our test is more rigorous than when using a glass calibration substrate. The maximum placement area simulated was 66x25 cm, representing an oversized PWB. The stand calibration procedure is for a 33x15 cm PWB. The typical placement pattern and the more demanding internal pattern are shown in Figure 6.

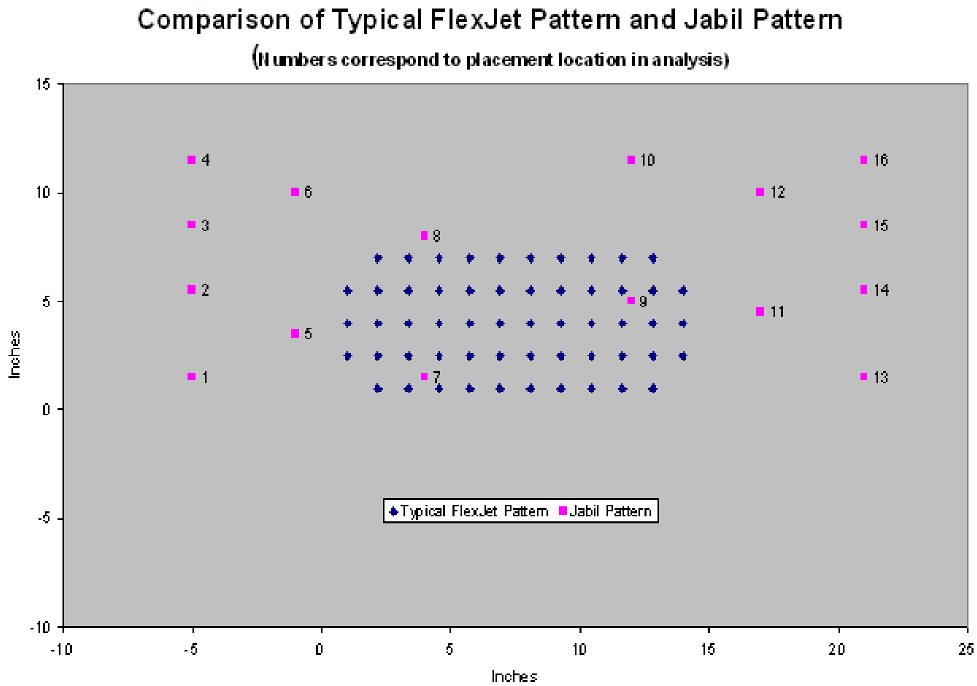

Figure 6. A comparison of typical component placement test patterns (blue dots) to the internal placement test (red squares).

The placement results are shown below:

Accuracy & repeatability data for QFP

Dimension	Mean	StDev	Spec	Cpk
XDev	26.57	5.35	75	3.02
YDev	24.08	8.17	75	2.08

Accuracy & repeatability data for 0402

Dimension	Mean	StDev	Spec	Cpk
XDev	20.48	11.63	100	2.28
YDev	2.95	12.97	100	2.49

In general the results were favorable and indicate that the placement equipment meets the current specification of C_{pk} >1.67[ii].

Solder print consistency was investigated for tin-lead solder paste printing with data gathered with EKRA 13 and SVS 8100 measuring systems. Lead-free solder paste printing was evaluated with only the SVS 8100. Statistical analysis was performed by using the t distribution to compare means, and the F and Cochran-Hartley criteria to compare variance. The alpha level was 0.05. Figures 7 and 8 are graphs of the statistical analysis. In these figures, case 1 is the comparison of a standard aperture for a 0402 passive to a 10% area reduced home plate design using lead-free solder, case 2 is a comparison of a 10% reduced home plate design between lead-free and tin-lead solder paste, and case 3 is a comparison of lead-free to leaded for a BGA aperture. All stencils were 5 mils (0.125 mm) thick. The threshold targets are the mauve columns, the blue columns are the actual data. The blue columns show that at a confidence level of 95% (alpha= 0.05) that there is no statistically significant difference in the data comparisons. Since this result was our objective, this evaluation was very positive.

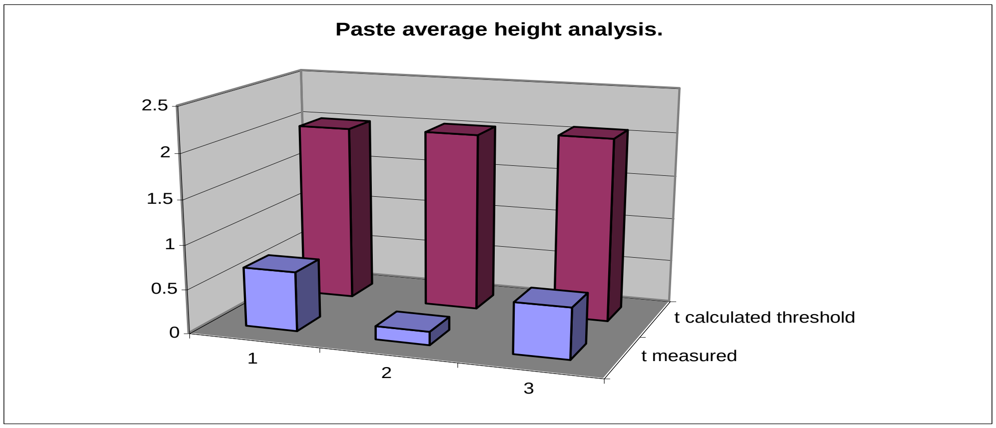

Figure 7. T test comparison of means for cases 1, 2, and 3.

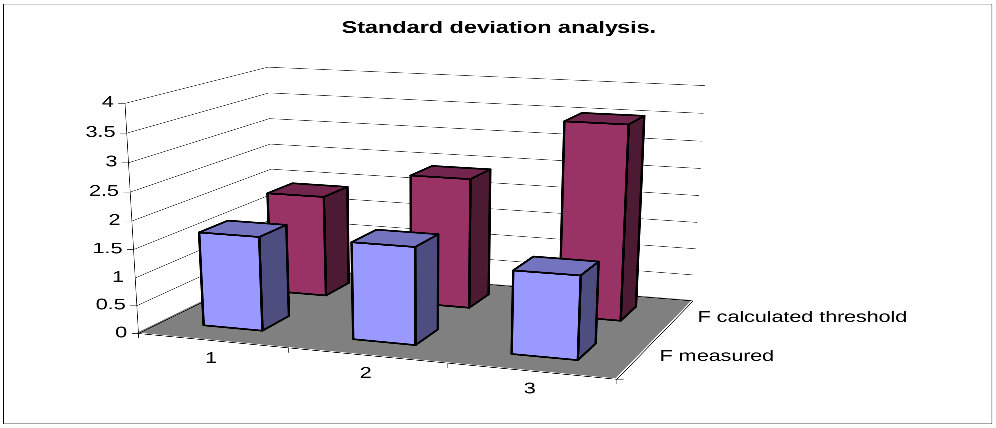

Figure 8. F test comparisons of variances for case 1, 2, and 3.

The SMT reflow soldering process can be broken down into three major components: equipment design, solder paste and the reflow temperature profile. Equipment analysis was conducted in two phases: preliminary screening to identify those machines most likely to meet large PWB assembly needs and then detailed analysis of two finalists. Among regular criteria used for oven evaluation—cross-belt uniformity, repeatability etc.—there were a few directly linked to RoHS soldering and temperature gradient minimization above liquidus. Both machines successfully demonstrated high temperature ability suitable for lead free soldering, but had very different characteristics (t, F alpha=0.05) for delta T (at the solder joints from the center to the corner of the PBGA) which can be explained by the difference in convection module design. The chosen oven design made a very important contribution into mitigating the tight production window challenge discussed above.

In establishing an optimum reflow profile, the following material criteria were considered:

- A high & long preheating cycle which can minimize temperature distribution above liquidus
- Very low ramp rate at the liquidus crossing, this feature along with slow preheating can mitigate tombstoning
- Stable slump characteristics to minimize solder beading failure modes for optimized land pattern design with reduced space between pads
- “Flat top” profiling shape (see Figure 9) above liquidus to suppress temperature spread and minimize temperature load on components and the PWB (recent studies of RoHS 6 PWB materials suggest that some PWBs are susceptible to high thermal load)
- Reasonable flux activity above liquidus for a temperature range starting as low as 235C with known / confirmed environmental reliability

Our preferred profile, displaying the above characteristics, is shown in Figure 9.

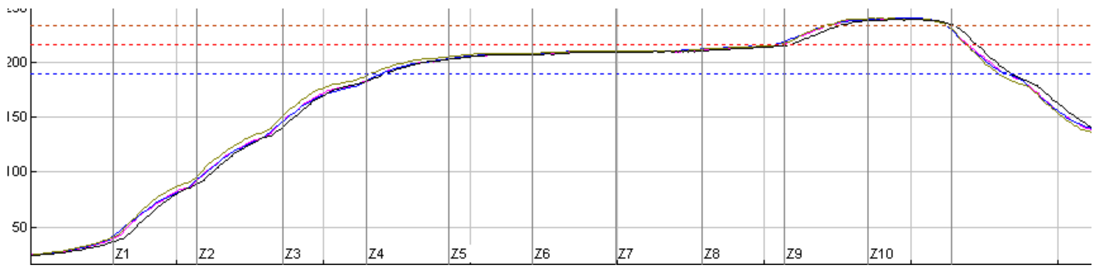

Figure 9. Preferred reflow profile for RoHS 6 assembly

The combination of the above described soldering profile with proper soldering materials and reflow equipment demonstrated very positive results as shown in the table below:

Product size	Component spread	RoHS level	T max spread	TAL spread
59x42x0.3 cm	**BGA 1936 - cap 0402**	**RoHS 6**	**236.1-246C**	**72.2-105.4 sec**
38x38x0.29 cm	**BGA 1521, 1517, 1508 - cap 0402**	**RoHS 6**	**234.9-241.8C**	**66.8-78.5 sec**
38x38x0.29 cm	**BGA 1521, 1517, 1508 - cap 0402**	**RoHS 5.5**	**223.7-231.5C**	**140.1-159 sec**

* All deltaT data above was inside the production window optimized for every component.

Successful assembly of these products confirmed our ability to minimize temperature variations above liquidus, even for challenging RoHS 5.5 assembly and achieve favorable results.

The Results

The work that has been discussed up to this point enabled us to produce products with RoHS solder joints as seen in Figures 10 (C0402 passive), 11 (SMT connector), and 12 (PBGA). Voiding was 100% monitored by 5DX X-ray system and did not exceed IPC specifications.

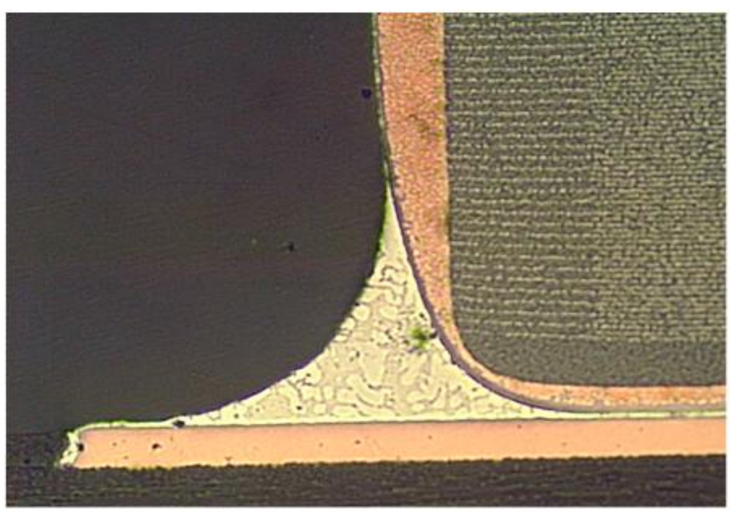

Figure 10. A RoHS 6 solder joint in a C0402

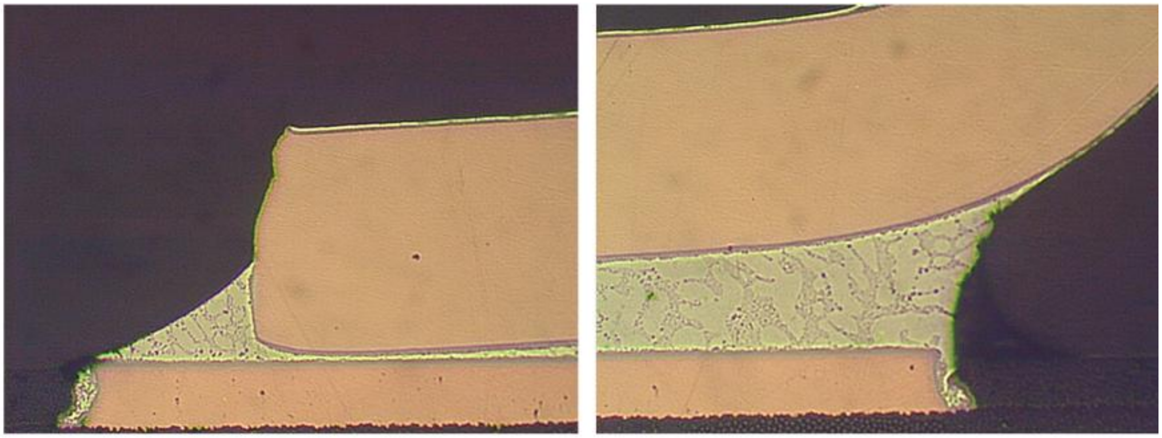

Figure 11. A RoHS 6 solder joint in a SMT connector

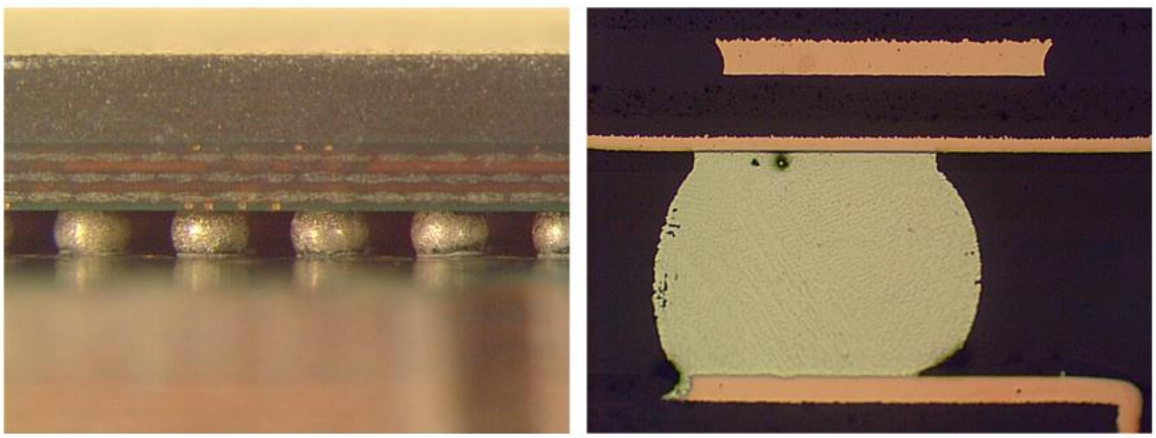

Figure 12. RoHS 6 PBGA solder joints

By implementing the work described in this paper, we have been able to assemble RoHS 6 products with a 56 cm PWB that is 0.3 cm thick and composed of 22 layers, 12 of them being power and ground planes. See Figure 13. This product has about 5500 component placements on the bottom side alone (more than 3000 of them C0402). The top side provides a wide specter of possible packages from a few BGAs with 1936 balls, down to QFNs and passives like the C0402. The product was developed at RoHS 5.5 and RoHS 6 levels. The 5.5 level provided more of a challenge due to its inability to be properly adjusted into a single acceptable process window, as a result of the compromise between approved RoHS 5 design and emergency RoHS 6 BGA applications. Leaded product spread reached a 75 cm long motherboard. We did not yet try it for a lead-free environment, due to the absence of such requirements.

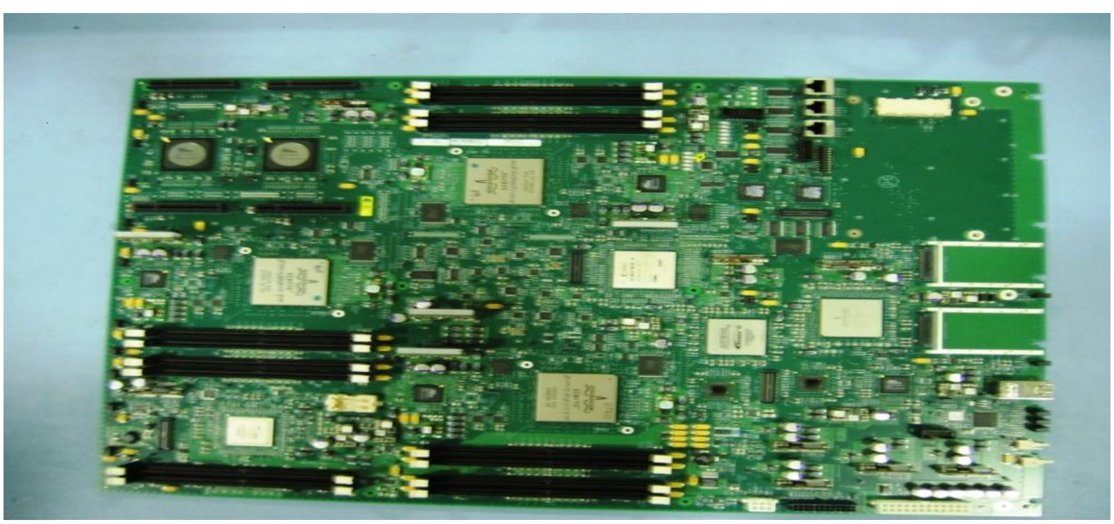

Figure 13. A RoHS 6 assembled PWB

Conclusion

By careful planning, working with our customers through the product life cycle, education, logistics control, and performing a considerable amount of engineering, we has been able to assemble RoHS 5, RoHS 5.5 and RoHS 6 under one roof. It is our hope that by sharing these experiences others will be helped to achieve this difficult task.

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[i] C_p = Total Tolerance/6 Sigma

[ii] C_{pk}= the minimum of: (mean-low spec limit)/3 sigma or (upper spec limit-mean)/3 sigma

Large Board Assembly in a RoHS 5, 5.5 and 6 Environment

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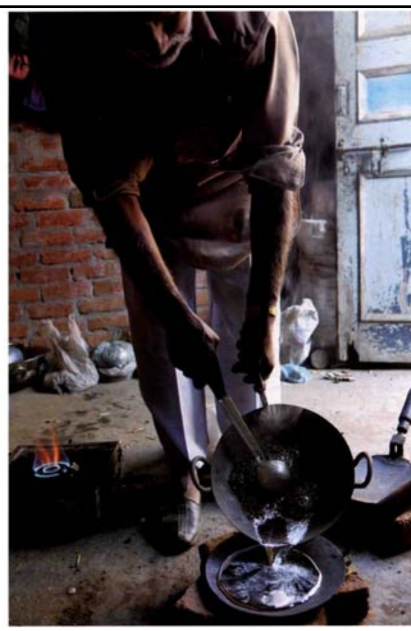
INDIUM CORPORATION OF AMERICA

Reminder: RoHS is to Make Recycling Easier

- "RoHS has been enacted for nearly two years and I don't feel safer"
- Objective: To assist recycling efforts set forth by WEEE

REUSE Workers strip picture tubes from thousands of used computer monitors piled at Monitex, a Grand Prairie, Texas, recycler. Tubes that work will be exported to a factory in Thailand, where they'll be used in low-cost TVs. Broken ones are recycled domestically.



TOXIC MELT In a poor suburb of New Delhi, India, where informal e-waste processing is a common household business, a man pours molten lead smelted from circuit boards. His family uses the same pots for cooking—a potentially deadly practice.

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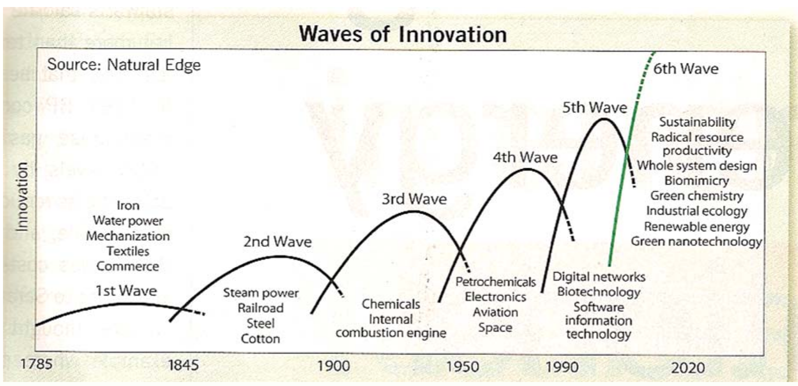
DUMPED A farmer in rural Taizhou, China, readies sweet potatoes for market beside circuit boards burned so metals could be extracted. The region has long been a major dump site for e-waste, but a crackdown by authorities has reduced illegal trade.

The Green Generation



Global Foundation, Business Week 02/04/08

Lead-Free Reliability Thought

- "Everyone knows there is no data on LF reliability right?"
- Wrong
  - $500 B of products made, some since 2001
    - No "sky is falling" reliability issues
  - $100M of R&D
- Long term (>5 years) data still sketchy

Jabil Billerica

- Medium to Large Facility
- Medium to Large size customers
- Broad Product Mix
- Special Expertise in large board assembly

RoHS 5, 5.5, 6

- RoHS 5 (tin-lead solder paste and components with tin-lead finished leads, the remaining hardware being RoHS compliant),
- RoHS 5.5 (RoHS 5 with BGAs that have SAC or SACX solder balls)
- RoHS 6 (fully compliant RoHS assembly)

Close Customer Relationship is Vital

- Education/Training both ways
- Agree on Deliverables
  - Technical Tasks
  - Materials Management
  - Documentation
- Designate an Owner/Watchdog to establish and track all deliverables/ concerns

Jabil Billerica

- Developed RoHS 5, 5.5, 6:
  - In one facility
  - For PWBs up to 56cm long and 0.3 cm thick
- Color coding established:
  - RoHS 6 is green
  - RoHS 5 is yellow
  - Used for all equipment, benches, racks, components, procedures, assembly space

Logistics Continued

- Even paperless documents are color coded and linked to latest waivers, deviations etc.
- Critical Issue: Reflow Temp Difference
  - RoHS 5: $T_m = 183^o$ C
  - RoHS 6: $T_m = 217^o$ C
  - Tolerance control tighter on RoHS 6

Component Concerns

- High Temperature Performance
- Engineering Change Orders (ECOs)
- Material Change Orders (MCOs)
- Color coding mandatory

Reflow Profile Challenges

- RoHS 6 Can Require a 5°C process window
- RoHS 5.5 must be hot enough to completely melt the solder balls
- SAC305 is standard alloy: T_m =217°C
- SAC105 creates more of a challenge
- T_m =227°C

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Sn/Pb Paste; SAC Ball

Backward Compatibility solder joints showed severe grain growth if the peak soldering temperature was below the lead free solder ball melting point.

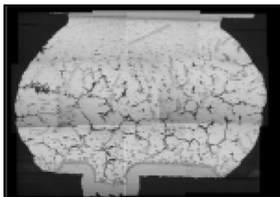

Figure 9a: Pb diffused along the grain boundary with reflow profile below the lead free solder ball melting point. Black/Grey – Pb Rich, Rod shape – Ag3Sn, Grey Particles – Cu6Sn5.

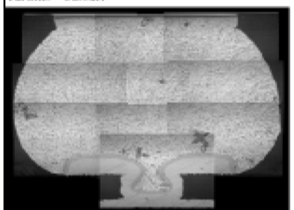

Figure 9b: The refined solder microstructure obtained when the peak reflow temperature is higher than (217°C) the melting point of 95Sn4.5Ag0.5Cu

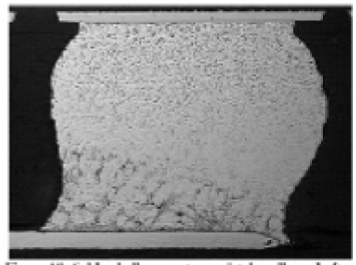

Figure 10: Solder ball was not completely collapsed after cooling and this led to abnormal joint shape (showing necking). Pb was not diffused throughout the whole solder joint.

C. Key Chung, Raiyo Aspandiar, K. Foo Leong, Cheng Siew Tay, "The Interactions of Lead (Pb) in Lead Free Solder (Sn/Ag/Cu) System", 52nd ECTC, S04-P7, San Diego, CA, May 28-31, 2002

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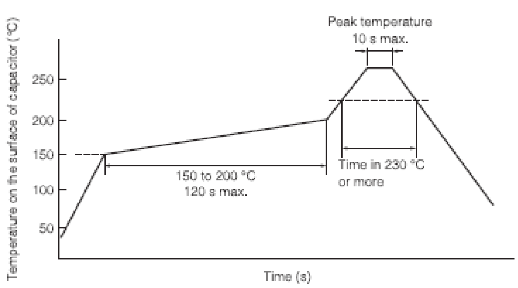
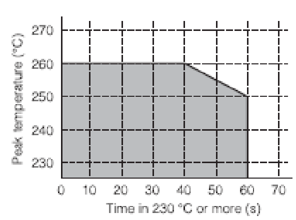
SAC RoHS 6 Reflow Process Window



EX.)

Peak temperature	Time in 230°C or more
260°C, 10s max.	40s max.
250°C, 10s max.	60s max.



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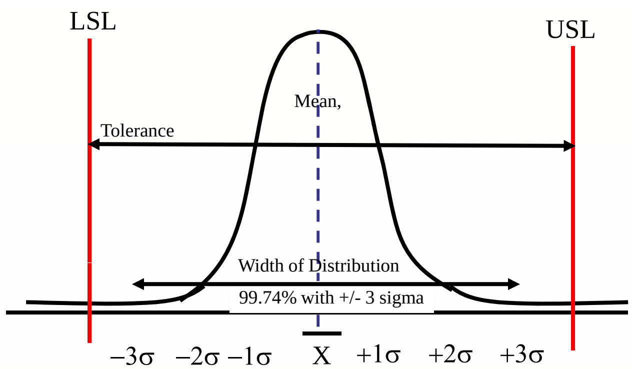
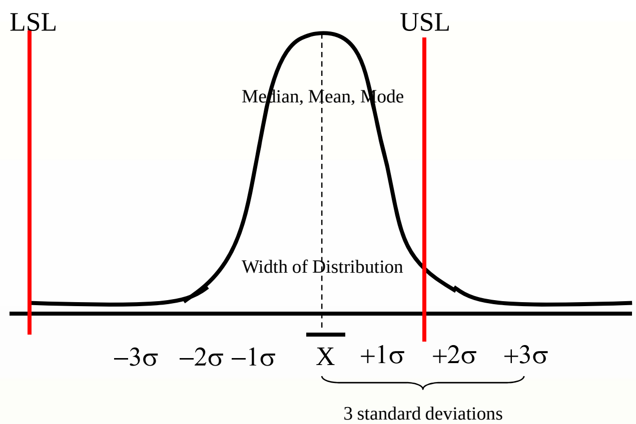
Large Board Challenges

- Goes Beyond IPC-9850 when PWB > 50 cm
- PWB dimensional stability and equipment tolerances are issues

Good C_p and C_{pk}



Good C_p, Poor C_{pk}

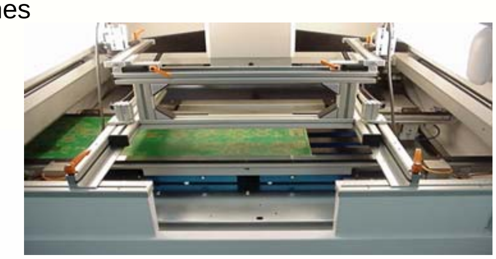


C_p and C_{pk}

- $C_p = \dfrac{USL - LSL}{6\sigma}$
- $C_{pu} = \dfrac{USL - Xbar}{3\sigma}$
- $C_{pl} = \dfrac{Xbar - LSL}{3\sigma}$
- $C_{pk} = \min(C_{pu}, C_{pl})$

Stencil Printer Evaluation

- Two Cameras
  - Load PWB and align 50 times
  - Fiducials 53.3 cm apart
  - Tolerance +/- 0.025 cm
  - 75 cm capable
- Results
  - $C_p X_1 = 8.28$
  - $C_p Y_1 = 2.23$
  - $C_p X_2 = 3.58$
  - $C_p Y_2 = 3.28$



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Component Placement

- 16 aluminum boards run
  - 2 fiducials
  - 0402 passives
  - 100 pin QFP Glass Slugs
  - Success Criteria C_{pk} >1.67
- Placement capable to 66x25 cm

Accuracy & repeatability data for QFP

Dimension	Mean	StDev	Spec	Cpk
XDev	26.57	5.35	75	3.02
YDev	24.08	8.17	75	2.08

Accuracy & repeatability data for 0402

Dimension	Mean	StDev	Spec	Cpk
XDev	20.48	11.63	100	2.28
YDev	2.95	12.97	100	2.49

Data in microns

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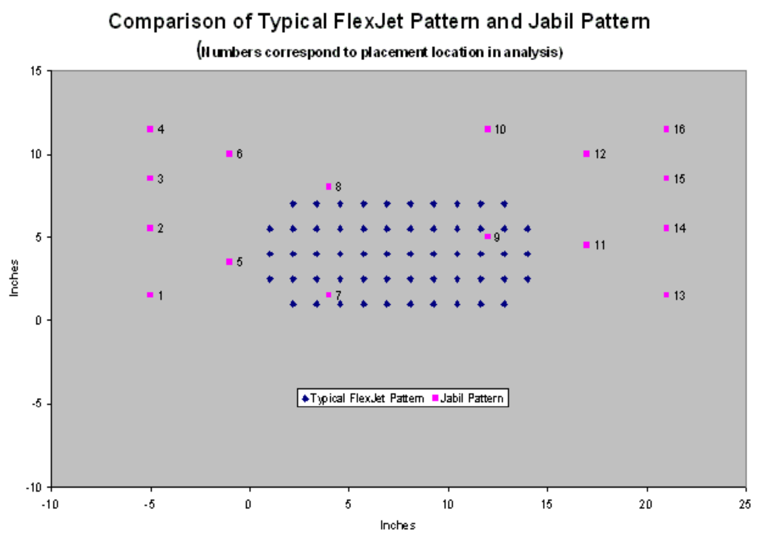
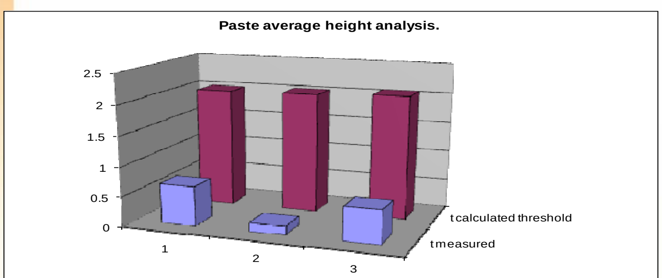


Solder Paste Consistency

- Volume Analysis with SVS 8100
  - 1 = Leaded Standard 0402 to Homeplate
  - 2 = Leaded to Lead-free Homeplate
  - 3 = Lead-free to leaded BGA
- Compare with t test



$$t_0 = \frac{\bar{x}_1 - \bar{x}_2}{s/\sqrt{n}}$$

< 2, values considered equal

Reflow Objectives

- A high & long preheating cycle which can minimize temperature distribution above liquidus
- Very low ramp rate at the liquidus crossing, this feature along with slow preheating can mitigate tombstoning
- Stable slump characteristics to minimize solder beading failure modes for optimized land pattern design with reduced space between pads
- “Flat top” profiling shape (see Figure) above liquidus to suppress temperature spread and minimize temperature load on components and the PWB (recent studies of RoHS 6 PWB materials suggest that some PWBs are susceptible to high thermal load)
- Reasonable flux activity above liquidus for a temperature range starting as low as 235C with known / confirmed environmental reliability

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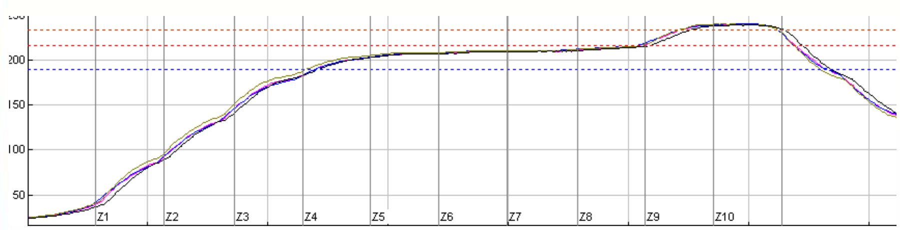
Preferred RoHS 6 Profile



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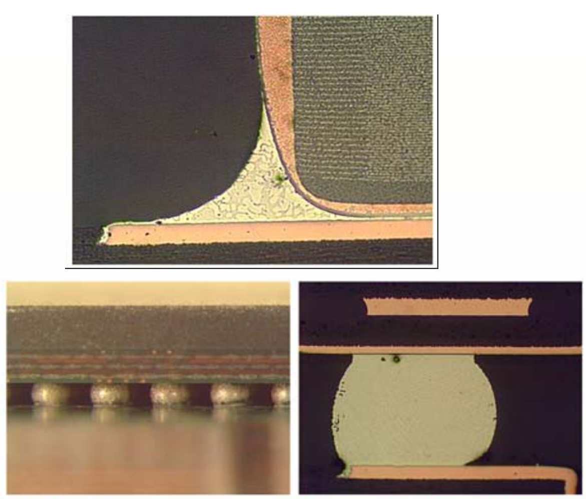
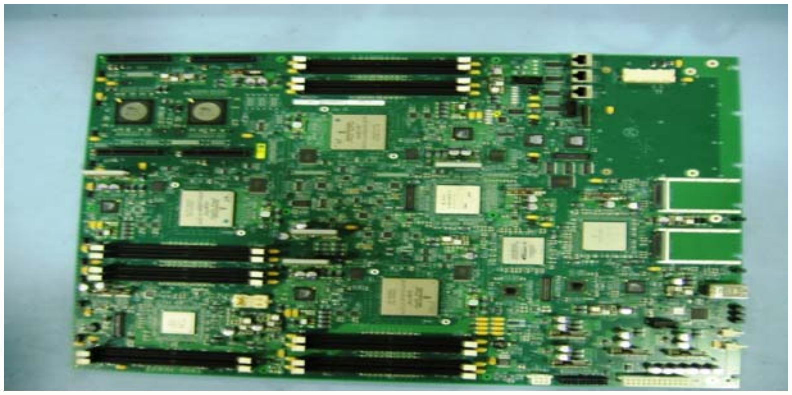
Profile Adjustments to Fit Product

Product size	Component spread	RoHS level	T max spread	TAL spread
59x42x0.3 cm	BGA 1936 - cap 0402	RoHS 6	236.1-246C	72.2-105.4 sec
38x38x0.29 cm	BGA 1521, 1517, 1508 - cap 0402	RoHS 6	234.9-241.8C	66.8-78.5 sec
38x38x0.29 cm	BGA 1521, 1517, 1508 - cap 0402	RoHS 5.5	223.7-231.5C	140.1-159 sec

The Results: RoHS 6 Solder Joints



Up to 0.3cm thick, 22 layers, 56 cm



Conclusions

- RoHS 5, 5.5, 6 Large Board assembly can be achieved with
  - Careful attention to logistics
    - Color coding and a product owner
    - Effective ECO and MCO control
  - Meticulous process development
    - Effective Printing and Placement Cp, Cpk
    - Careful Product Specific Reflow Profile Development