CHOOSING THE RIGHT LEAD-FREE SOLDER FOR HI-REL PRINTED WIRING ASSEMBLIES

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ABSTRACT

The use of lead in electronics has come under increasing scrutiny. Given the trends in both Japan and Europe, it is highly likely that the U.S. will be driven by commercial interests to phase out lead (chemical symbol: Pb) in electronics usage. This paper presents data collected from a recent NASA project that focuses specifically on finding suitable alternatives to eutectic tin-lead solders, especially in solder paste applications. The first phase of this project dealt with determining the most feasible candidates to replace tin-lead and to determine suitable processing operations in assembling printed wiring boards (PWBs). No problems were encountered during the manufacturing process with the lead-free pastes.

KEY WORDS: Manufacturing/Fabrication/Processing; Electrical and Electronic; Lead-free Processes (LFP).

1. INTRODUCTION

Lead-containing solder has been used for past 60 years as the principal joining material for Level 2 packaging defined as attaching component level packages to a suitable substrate to produce printed wiring assemblies (PWAs). Generally the solder of choice has been either eutectic tin-lead solder containing 63 wt. percent tin (Sn) and 37 wt. percent lead (Pb) or near-eutectic tin-lead solder containing 60 wt. percent tin and 40 wt. percent lead. Eutectic tin-lead solder has a unique melting point of 183°C (361°F), whereas near-eutectic tin-lead solder melts within the range of 183°-189°C (361°-372°F).

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Tin-lead solder forms stable solder joints capable of operating in a wide variety of service environments. It is easy to use, and because it has a relatively low melting point, rework and repair are also easy. In addition, the reliability of tin-lead solder joints is well understood. Using Coffin-Manson curves and Weibull distribution plots of thermally cycled solder joints, it is possible to estimate the amount of useful life remaining for tin-lead solder joints after exposure to a known number of thermal cycles.

It is widely recognized that the use of lead in electronics accounts for only a very small percentage of lead used worldwide. Possibly only 2-3% of the lead utilized in manufactured products ends up in electronic products. Nevertheless, the fear is that lead-containing electronic products will ultimately find their way into landfills. As a consequence, the lead could be leached out and end up in ground water reservoirs. The issue is now moving out of the technical arena into the political one. Once nontechnical considerations dominate, it makes very little difference what the technical realities are since they tend to be obscured by political and social perceptions.

In fact, the movement to eliminate lead shows the ever-growing importance of what is called Design for the Environment (DfE) and Green Manufacturing. Both emphasize the use of environmentally benign materials so that the environment is impacted as little as possible.

Although a number of potential substitutes for tin-lead solder already exist, there is no simple drop-in replacement for this material. All substitutes have properties somewhat divergent from that of tin-lead and will require both process development and validation. In electronics, the impact will be felt by bare printed wiring boards, components, and electronic card assemblies. Compared to tin-lead solder, these other solder materials display both advantages and drawbacks. This situation is analogous historically to what took place when the search was initiated to find suitable substitutes for chlorofluorocarbons (CFCs) back in the early '90s where the driver was to find substances having low or zero ozone depletion potential (ODP).

2. BACKGROUND

Almost all viable lead-free candidate alloys have melting points greater than 200°C but below that of pure tin, which has a melting point of 232°C (449°F). About one year ago, NASA funded a project to begin searching for suitable candidates under the aegis of the NASA Electronic Parts and Packaging (NEPP).

Four lead-free solder pastes were selected based on an extensive search of the literature. These are given below in Table 1. Two PWBs per solder type were assembled using the four different solder pastes resulting in total of eight circuit card assemblies.

Table 1 Lead-free solder alloys for Phase I processing

Composition	T_m (°C)	Advantages	Potential issues
1) Sn96.5Ag3.5 (eutectic)	221	a) Good wetting characteristics and superior joint strength compared to Sn/Pb solder b) Long history of use	a) May exhibit structural weakness at solder connection b) High T_m
2) Sn95.5Ag3.8Cu0.7	217-218	a) Recommended by NEMI b) Virtually no plastic range c) Rapid solidification avoiding formation of cracks d) Formation of intermetallics $Cu6Sn_5$ and Ag_3 Sn provide greater strength and fatigue resistance than Sn/Pb solder	a) High T_m
3) Sn96.2Ag2.5Cu0.8Sb0.5 (Castin®)	217-218	a) Addition of Sb improves thermal fatigue b) Solder coating offers flatter pads and uniform coat c) Works well with Ni/Au Ag/Pd and OSP boards d) Sb slightly reduces melting temperature and refines grain structure	a) Sb trioxide may exhibit toxicity at higher temperatures b) High T_m
4) Sn77.2In20.0Ag2.8 (Indalloy 227®)	175(T_S)-187(T_L)	a) Compatible T_m to Sn/Pb b) Good ductility, strength and creep resistance c) Low dross in wave solder	a) Supply and cost may be prohibitive factors in its use. b) 118°C eutectic point may deteriorate mechanical properties of solder joints c) Large plastic range

3. OBJECTIVES

The objectives of the overall task, which is composed of two phases, are two-fold.

3.1 Objective of Phase I Ensure that the four lead-free pastes listed in Table 1 could be successfully assembled. An important issue was whether printed wiring boards (PWBs) and components could be processed at the higher process temperatures (30°-35°C greater than for eutectic tin-lead). This was the key objective of the first year of the project (Phase I). Eight PWBs (two PWBs per paste) using the four different solder pastes per Table 1 were assembled. The results are given below and are the chief subject of this paper.

Based on the results obtained from processing the initial four pastes, two pastes will be selected to continue into Phase II.

3.2 Objective of Phase II Four PWBs per paste (2 pastes) will be assembled and thermal cycled. The exact thermal cycle is still to be determined. In addition, four PWBs produced with eutectic tin-lead paste will be assembled and thermal cycled as a control lot. Assemblying these twelve PWBs, thermal cycling them, and assessing the solder joint reliability is the principal objective of the second year of the project (Phase II).

At this point, the particular thermal cycle to be used in Phase II has not yet been decided upon. There are several types of thermal cycles being used depending upon the product and the industry. These are described in IPC-9701. Some of them are:

- JPL Cycle: -55°C to 100°C;
- Military Cycle: -55°C to 125°C;
- Commercial: 0°C to 100°C.

4. PERTINENT PROCESS INFORMATION

The following JPL process information is pertinent to the discussion. In general, low volume surface mount technology (SMT) manufacturing methods pertaining to high reliability printed wiring assemblies (PWAs) were employed.

4.1 Rosin-based Fluxes and Pastes Rosin-based fluxes and pastes are used to produce all electronic hardware. Using the terminology of Mil-F-14256, the classification of these products is rosin mildly activated (RMA).

4.2 Semi-automated Screen Printing The solder paste is applied using a semi-automated screen printer ensuring that the paste is deposited in a uniform and consistent manner. Only stainless steel stencils are used in conjunction with a stainless steel squeegee. All boards are visually inspected for proper paste deposition after the stencil operation. A laser-based solder paste height and width measurement system is used with a resolution of 0.0001 inch (2.5 μm). This system provides real time information on the uniformity of solder paste deposition. All boards are subjected to this measurement prior to the reflow operation.

4.3 Automated Placement Machine An automated placement machine is used to place parts on the printed wiring board (PWB).

4.4 Batch Vapor Phase Reflow Machine A batch vapor phase reflow operation was used to create the solder joints of the SMT PWAs. The SMT PWAs are thermally profiled using a M.O.L.E.® A thermocouple was attached to the PWB and to the M.O.L.E., which is a microprocessor-based data logger attached to a computer. Thermal profiling was done to eliminate thermal shock during preheat and reflow. This operation consisted of a vapor phase reflow machine using a constant boiling perfluorocarbon material—under a proprietary name with b.p. 240°C—for soldering the lead-free SMT PWAs. The PWAs were preheated to remove paste volatiles and to initiate the activation stage of the paste. The reflow liquid, since it boils at a constant temperature, minimizes the possibility of overheating the PWAs during reflow and ensures that the vapor blanket performs a uniform and consistent soldering operation. For eutectic tin-lead pastes and Indalloy 227, 3M Perfluorocompound® FC-5312 having a boiling point of 216°C was used.

5. EXPERIMENTAL

5.1 Packages Used on Test PWBs Double-sided test PWBs with footprints for various chip components and IC packages, including BGAs, were assembled. Figures 1 and 2 depict the bottom and top side respectively of the bare test PWB. Figures 3 and 4 depict the bottom and top side respectively of PWA001, assembled with Sn95.5Ag3.8Cu0.7. Figures 5 and 6 depict the bottom and top side respectively of PWA003, assembled with Sn96.2Ag2.5Cu0.8Sb0.5. See below. The BGAs were daisy-chained. The various component package types used and the number of each per PWB were as follows:

- Chip resistor, 0603 package (24 each per board);
- Chip resistor, 1206 package (18 each per board);
- SOT 23 package (2 each per board);
- SOIC 20 package, 50 mil pitch (2 each per board);
- PLCC 68 package, 50 mil pitch (1 each per board);
- QFP 100, 25 mil pitch (1 each per board);
- QFP 208 package, 20 mil pitch (1 each per board);
- BGA 225 full array package, 1.5 mm ball pitch (1 each per board);
- BGA 352 area array package, 1.27 mm ball pitch (1 each per board).

5.2 Pre-assembly Inspection and Test Prior to assembly, all the BGA pads on the PWBs were checked to ensure the daisy-chain integrity, and in addition, all BGA components were checked to ensure the daisy-chain integrity. All eight PWBs and one sample of each component were tested with scanning acoustic microscopy (SAM) to obtain a signature prior to assembly.

5.3 PWB and Component Preparation All PWBs were cleaned in a centrifugal cleaner using an aqueous-based chemistry. This chemistry consists of a 20% solution of a proprietary blend of alcoxypropanols and amine compounds in DI water with 1% corrosion inhibitor and 0.1% defoamer. The cleaning cycle and its parameters were as follows.

- Purge the wash chamber with nitrogen gas for one minute;
- A wash cycle of 5 minutes duration using Vigon A200 solution heated to 50°C;
- A rinse cycle of 10 minutes duration using DI water heated to 50°C;
- A dry cycle of 5 minutes duration using air heated to 180°C;
- A vacuum oven bake cycle for 8 hours at 100°C.

5.4 Screen Printing PWBs were screen printed with four different pastes. See Table 2.

Table 2 Four Pb-free solder pastes used

Item	Paste composition	PWB serial number
1	Sn95.5Ag3.8Cu0.7	PWA001 and PWA002
2	Sn96.2Ag2.5Cu0.8Sb0.5 (Castin®)	PWA003 and PWA004
3	Sn96.5Ag3.5 (eutectic)	PWA005 and PWA006
4	Sn77.2In20.0Ag2.8 (Indalloy 227®)	PWA007 and PWA008

5.4.1 Printing Parameters The printing parameters were as follows:

- Stencil Type— Stainless steel with foil thickness of 7 mils;
- Squeegee Type —metal blade;
- Squeegee pressure setting — 5.6 kg;
- Squeegee speed — 15 mm per second.

Paste height was measured using 3-D a laser-based measurement system.

5.5 Component Placement Components were placed on side 1 (top side) using an automated placement machine. A split-vision rework system was used for component placement on side 2 (bottom side).

5.6 Solder Paste Reflow Two types of vapor phase reflow systems were used to reflow the solder pastes. Both consisted of an infrared preheating zone followed by a constant temperature boiling vapor zone. Pastes 1–3 (listed in Table 2) were reflowed using a bench top vapor phase system containing the perfluorocarbon material with a boiling point of 240°C. Paste 4 was reflowed using a stand-alone system containing a perfluorocarbon material with a boiling point of 216°C. A thermal profile was generated for each system. Assemblies were preheated to approximately 158°C at the rate of 0.88°C/sec followed by vapor phase reflow. The dwell time above liquidus was 62 seconds.

5.7 Post Reflow Cleaning All PWAs were cleaned in the centrifugal cleaning system using the cleaning cycle and cleaning chemistry described in Section 5.3 above.

5.8 Cleanliness Testing After processing, all PWAs were tested for ionic contamination level using a suitable ionic contamination tester. The cleanliness levels achieved per PWA are presented in Table 3 below. The results are presented in microgram per square centimeter ($\mu g/cm^2$).

5.8.1 Ionic Cleanliness Cutoff Limit The ionic cleanliness cutoff limit per JPL specifications is 1.55 $\mu g/cm^2$. All assemblies must have a contamination level less than this; otherwise, they are recleaned and tested. These processes are repeated until the ionic cleanliness level is less than 1.55 $\mu g/cm^2$.

Table 3 Ionic contamination levels

PWA S/N	Solder paste composition	Amount of ionic contamination μg/cm^2
S/N 001	Sn95.5Ag3.8Cu0.7	0.050
S/N 002	Sn95.5Ag3.8Cu0.7	0.051
S/N 003	Sn96.2Ag2.5Cu0.8Sb0.5 (Castin®)	0.008
S/N 004	Sn96.2Ag2.5Cu0.8Sb0.5 (Castin®)	0.008
S/N 005	Sn96.5Ag3.5 (eutectic)	0.040
S/N 006	Sn96.5Ag3.5 (eutectic)	0.029
S/N 007	Sn77.2In20.0Ag2.8 (Indalloy 227®)	0.260
S/N 008	Sn77.2In20.0Ag2.8 (Indalloy 227®)	0.198

5.8.2 Processing After Cleanliness Testing After cleanliness testing, all PWAs were baked in a vacuum oven at 70°C for 30 minutes.

5.9 Visual Inspection and X-Ray All PWAs were inspected under a microscope at 12 X magnification. The observations made are as follows:

- The solder flow generally appeared good except that the solder appeared grainier compared to Sn/Pb solder joints.
- The solder joints containing indium were even more grainy than the other three types of joints.
- There was one solder bridge at the corner on S/N 008.

5.10 Scanning Acoustic Microscopy All PWAs were examined with a scanning acoustic microscope to reveal the post assembly signature of the boards. The tests are being conducted and the results are not available at this time.

6. CONCLUSIONS

The following conclusions can be drawn.

- A longer delay was required for the first three pastes—the ones with a higher processing temperature—during the reflow process.
- No problems were encountered during the printing process with the lead-free pastes. The printing was uniform for all PWBs.
- Although the solder fillets looked good, the solder joints appeared grainier than those formed by Sn63/Pb37 solder.
- The ionic cleanliness levels of all assemblies processed with lead-free pastes were well below the 1.55 μg/cm^2 acceptability limit.
- The daisy-chain continuity measured after reflow was the same as that prior to the reflow, meaning there were no opens after reflow.

6.1 Overall Conclusion No problems were encountered during the manufacturing process with the lead-free pastes. Phase II was initiated in October of 2002.

7. SUMMARY

The use of lead-free pastes to assemble PWBs seems feasible from a process point of view. However, new QA criteria will have to be devised for lead-free solder joints due to the grainy nature of their appearance.

8. FUTURE PLANS

In the upcoming Phase II tests, the two most promising lead-free pastes will be used. The selection will be based on both technical issues and best industry practices (BIP) issues. At this point, the two most likely candidates are:

1) Sn95.5Ag3.8Cu0.7 or possibly some other slightly different alloy containing tin, silver, and copper.
2) Sn96.2Ag2.5Cu0.8Sb0.5

Four PWB assemblies per paste will be built, and four PWB assemblies using eutectic tin-lead paste will also be built as a control. These PWAs will be subjected to thermal cycling and vibration tests.

9. ACKNOWLEDGEMENTS

The research to investigate lead-free soldering and finding a suitable lead-free candidate to replace eutectic tin-lead was performed at the Surface Mount Technology Laboratory at the Jet Propulsion Laboratory, California Institute of Technology, under a contract with the National Aeronautics and Space Administration. The authors would like to thank Messrs. Philip Zulueta, Charles Bodie, and Amin Mottiwala for their support.

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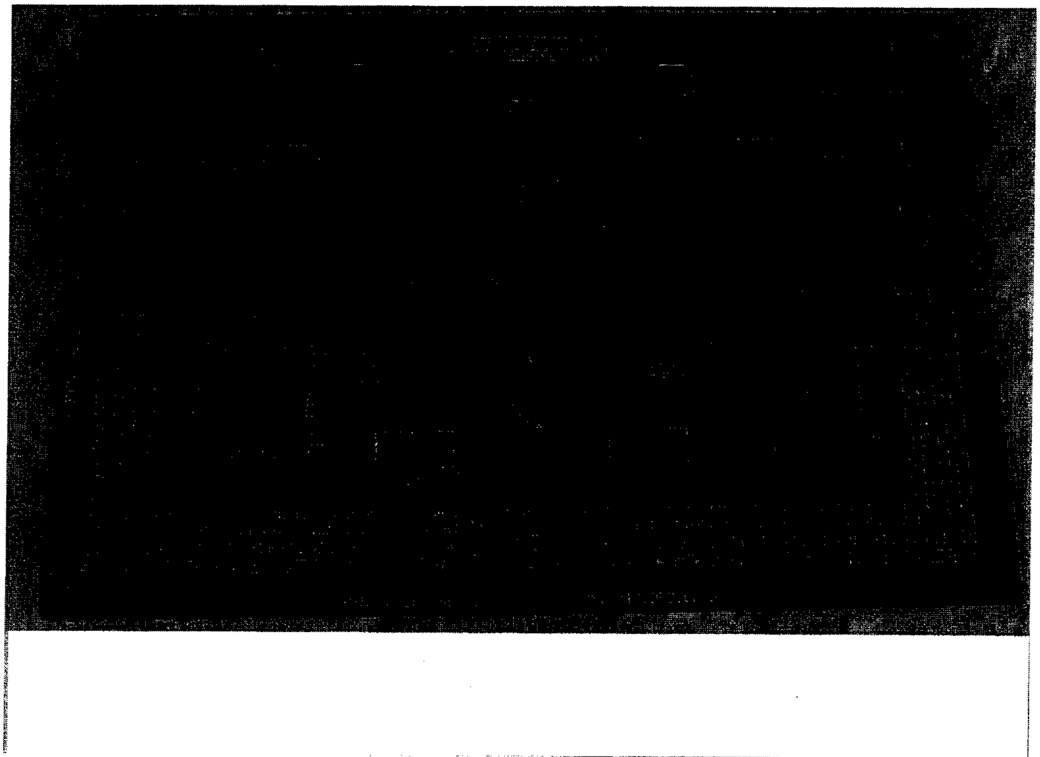

Figure 1 Bottom side of the test PWB

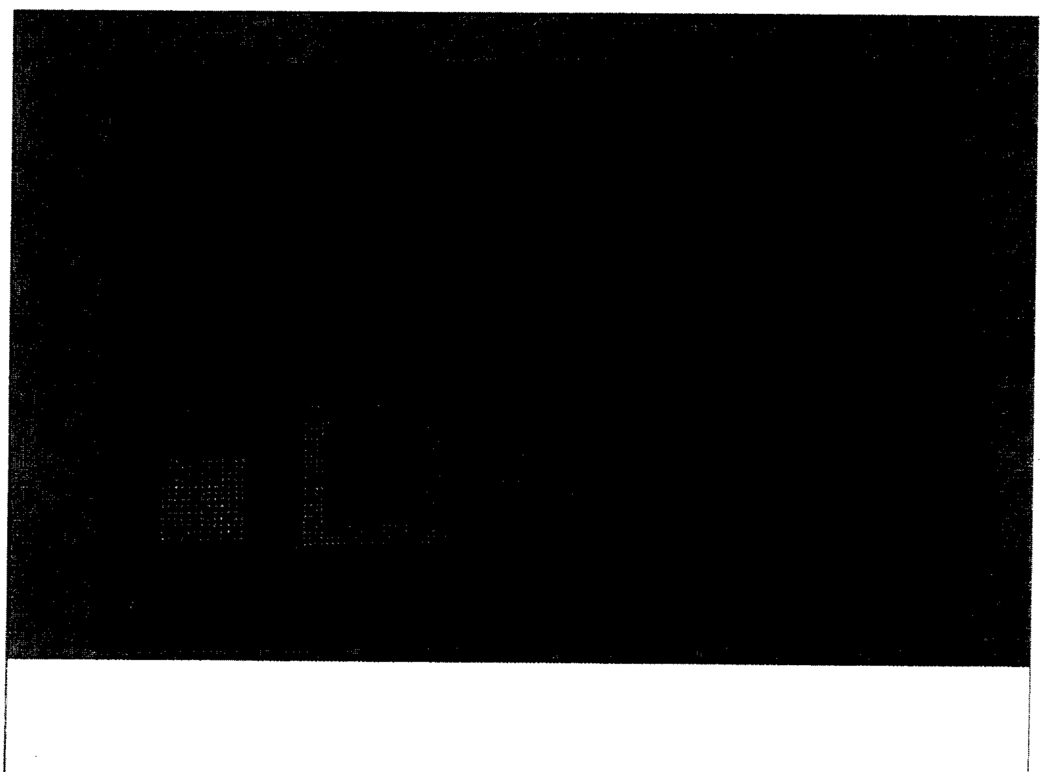

Figure 2 Top side of the test PWB

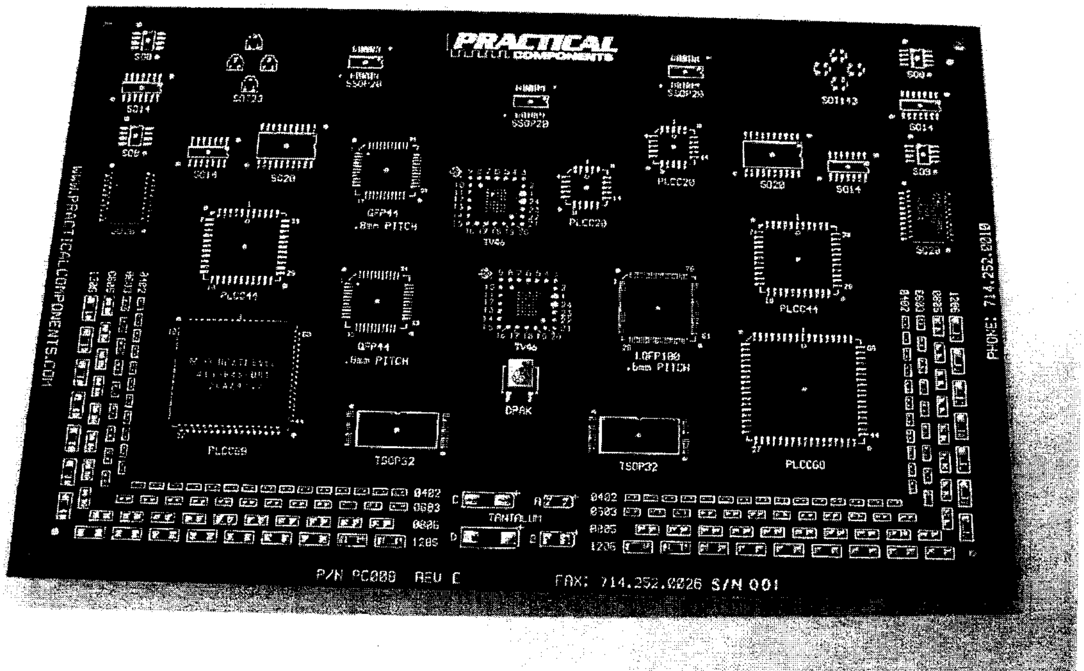

Figure 3 Bottom side of test PWB assembled with Sn95.5Ag3.8Cu0.7 (PWA001)

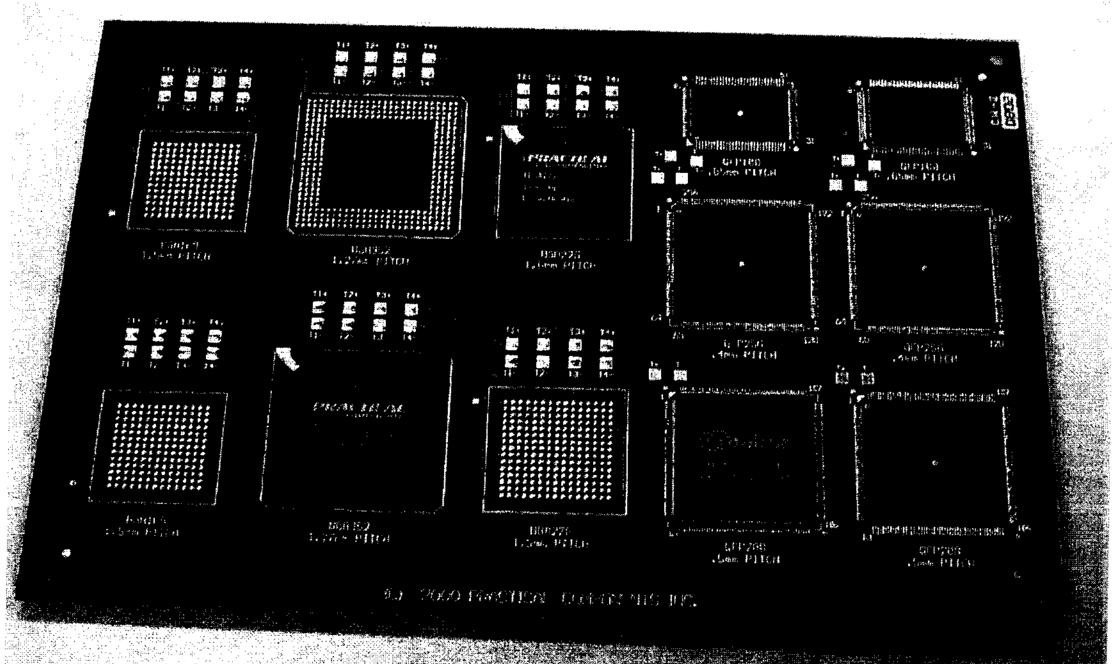

Figure 4 Top side of test PWB assembled with Sn95.5Ag3.8Cu0.7 (PWA001)

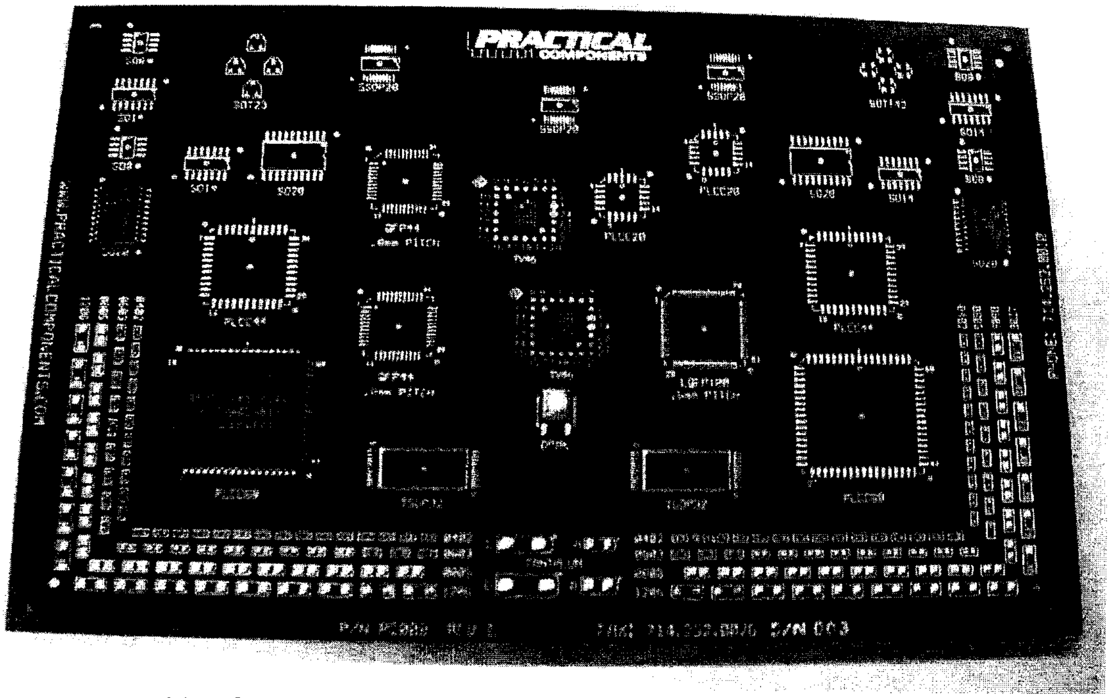

Figure 5 Bottom side of test PWB assembled with Sn96.2Ag2.5Cu0.8Sb0.5 (PWA003)

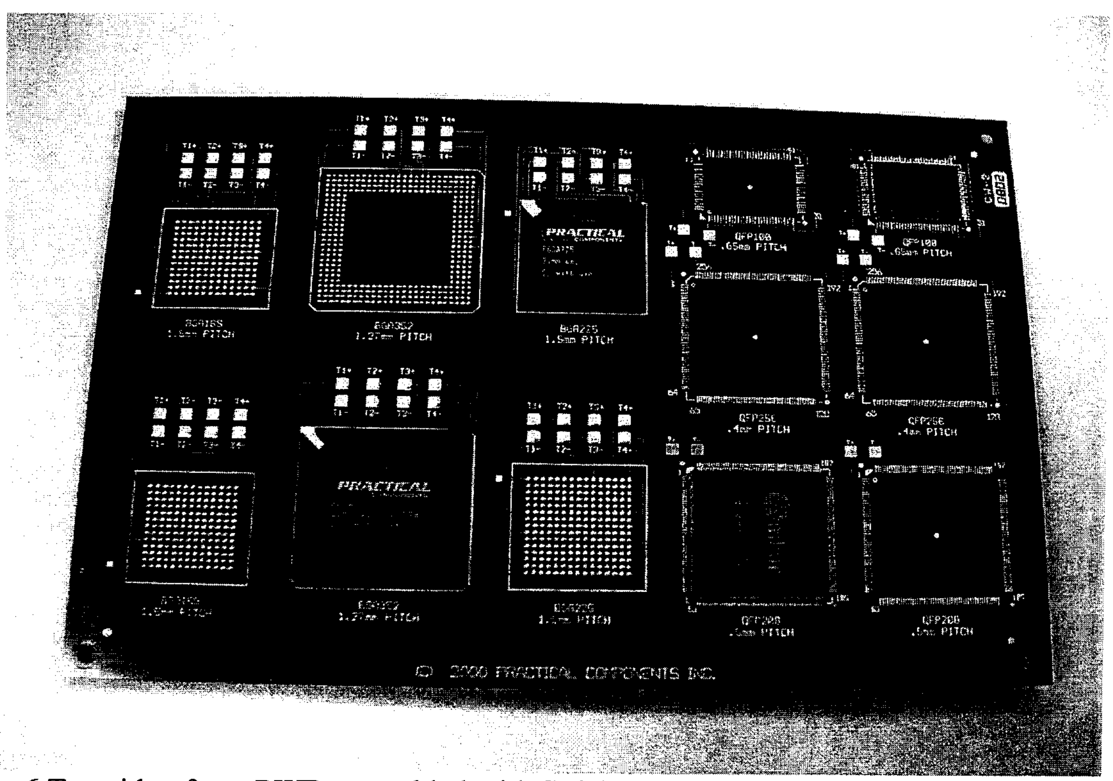

Figure 6 Top side of test PWB assembled with Sn96.2Ag2.5Cu0.8Sb0.5 (PWA003)

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- BGA 225 full array package, 1.5 mm ball pitch (1 each per board);
- BGA 352 area array package, 1.27 mm ball pitch (1 each per board).

5.2 Pre-assembly Inspection and Test Prior to assembly, all the BGA pads on the PWBs were checked to ensure the daisy-chain integrity, and in addition, all BGA components were checked to ensure the daisy-chain integrity. All eight PWBs and one sample of each component were tested with scanning acoustic microscopy (SAM) to obtain a signature prior to assembly.

5.3 PWB and Component Preparation All PWBs were cleaned in a centrifugal cleaner using an aqueous-based chemistry. This chemistry consists of a 20% solution of a proprietary blend of alcoxypropanols and amine compounds in DI water with 1% corrosion inhibitor and 0.1% defoamer. The cleaning cycle and its parameters were as follows.

- Purge the wash chamber with nitrogen gas for one minute;
- A wash cycle of 5 minutes duration using Vigon A200 solution heated to 50°C;
- A rinse cycle of 10 minutes duration using DI water heated to 50°C;
- A dry cycle of 5 minutes duration using air heated to 180°C;
- A vacuum oven bake cycle for 8 hours at 100°C.

5.4 Screen Printing PWBs were screen printed with four different pastes. See Table 2.

Table 2 Four Pb-free solder pastes used

Item	Paste composition	PWB serial number
1	Sn95.5Ag3.8Cu0.7	PWA001 and PWA002
2	Sn96.2Ag2.5Cu0.8Sb0.5 (Castin®)	PWA003 and PWA004
3	Sn96.5Ag3.5 (eutectic)	PWA005 and PWA006
4	Sn77.2In20.0Ag2.8 (Indalloy 227®)	PWA007 and PWA008

5.4.1 Printing Parameters The printing parameters were as follows:

- Stencil Type— Stainless steel with foil thickness of 7 mils;
- Squeegee Type —metal blade;
- Squeegee pressure setting — 5.6 kg;
- Squeegee speed — 15 mm per second.

Paste height was measured using 3-D a laser-based measurement system.

5.5 Component Placement Components were placed on side 1 (top side) using an automated placement machine. A split-vision rework system was used for component placement on side 2 (bottom side).

5.6 Solder Paste Reflow Two types of vapor phase reflow systems were used to reflow the solder pastes. Both consisted of an infrared preheating zone followed by a constant temperature boiling vapor zone. Pastes 1–3 (listed in Table 2) were reflowed using a bench top vapor phase system containing the perfluorocarbon material with a boiling point of 240°C. Paste 4 was reflowed using a stand-alone system containing a perfluorocarbon material with a boiling point of 216°C. A thermal profile was generated for each system. Assemblies were preheated to approximately 158°C at the rate of 0.88°C/sec followed by vapor phase reflow. The dwell time above liquidus was 62 seconds.

5.7 Post Reflow Cleaning All PWAs were cleaned in the centrifugal cleaning system using the cleaning cycle and cleaning chemistry described in Section 5.3 above.

5.8 Cleanliness Testing After processing, all PWAs were tested for ionic contamination level using a suitable ionic contamination tester. The cleanliness levels achieved per PWA are presented in Table 3 below. The results are presented in microgram per square centimeter ($\mu g/cm^2$).

5.8.1 Ionic Cleanliness Cutoff Limit The ionic cleanliness cutoff limit per JPL specifications is 1.55 $\mu g/cm^2$. All assemblies must have a contamination level less than this; otherwise, they are recleaned and tested. These processes are repeated until the ionic cleanliness level is less than 1.55 $\mu g/cm^2$.

Table 3 Ionic contamination levels

PWA S/N	Solder paste composition	Amount of ionic contamination μg/cm^2
S/N 001	Sn95.5Ag3.8Cu0.7	0.050
S/N 002	Sn95.5Ag3.8Cu0.7	0.051
S/N 003	Sn96.2Ag2.5Cu0.8Sb0.5 (Castin®)	0.008
S/N 004	Sn96.2Ag2.5Cu0.8Sb0.5 (Castin®)	0.008
S/N 005	Sn96.5Ag3.5 (eutectic)	0.040
S/N 006	Sn96.5Ag3.5 (eutectic)	0.029
S/N 007	Sn77.2In20.0Ag2.8 (Indalloy 227®)	0.260
S/N 008	Sn77.2In20.0Ag2.8 (Indalloy 227®)	0.198

5.8.2 Processing After Cleanliness Testing After cleanliness testing, all PWAs were baked in a vacuum oven at 70°C for 30 minutes.

5.9 Visual Inspection and X-Ray All PWAs were inspected under a microscope at 12 X magnification. The observations made are as follows:

- The solder flow generally appeared good except that the solder appeared grainier compared to Sn/Pb solder joints.
- The solder joints containing indium were even more grainy than the other three types of joints.
- There was one solder bridge at the corner on S/N 008.

5.10 Scanning Acoustic Microscopy All PWAs were examined with a scanning acoustic microscope to reveal the post assembly signature of the boards. The tests are being conducted and the results are not available at this time.

6. CONCLUSIONS

The following conclusions can be drawn.

- A longer delay was required for the first three pastes—the ones with a higher processing temperature—during the reflow process.
- No problems were encountered during the printing process with the lead-free pastes. The printing was uniform for all PWBs.
- Although the solder fillets looked good, the solder joints appeared grainier than those formed by Sn63/Pb37 solder.
- The ionic cleanliness levels of all assemblies processed with lead-free pastes were well below the 1.55 $\mu g/cm^2$ acceptability limit.
- The daisy-chain continuity measured after reflow was the same as that prior to the reflow, meaning there were no opens after reflow.

6.1 Overall Conclusion No problems were encountered during the manufacturing process with the lead-free pastes. Phase II was initiated in October of 2002.

7. SUMMARY

The use of lead-free pastes to assemble PWBs seems feasible from a process point of view. However, new QA criteria will have to be devised for lead-free solder joints due to the grainy nature of their appearance.

8. FUTURE PLANS

In the upcoming Phase II tests, the two most promising lead-free pastes will be used. The selection will be based on both technical issues and best industry practices (BIP) issues. At this point, the two most likely candidates are:

1) Sn95.5Ag3.8Cu0.7 or possibly some other slightly different alloy containing tin, silver, and copper.
2) Sn96.2Ag2.5Cu0.8Sb0.5

Four PWB assemblies per paste will be built, and four PWB assemblies using eutectic tin-lead paste will also be built as a control. These PWAs will be subjected to thermal cycling and vibration tests.

9. ACKNOWLEDGEMENTS

The research to investigate lead-free soldering and finding a suitable lead-free candidate to replace eutectic tin-lead was performed at the Surface Mount Technology Laboratory at the Jet Propulsion Laboratory, California Institute of Technology, under a contract with the National Aeronautics and Space Administration. The authors would like to thank Messrs. Philip Zulueta, Charles Bodie, and Amin Mottiwala for their support.

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Figure 1 Bottom side of the test PWB

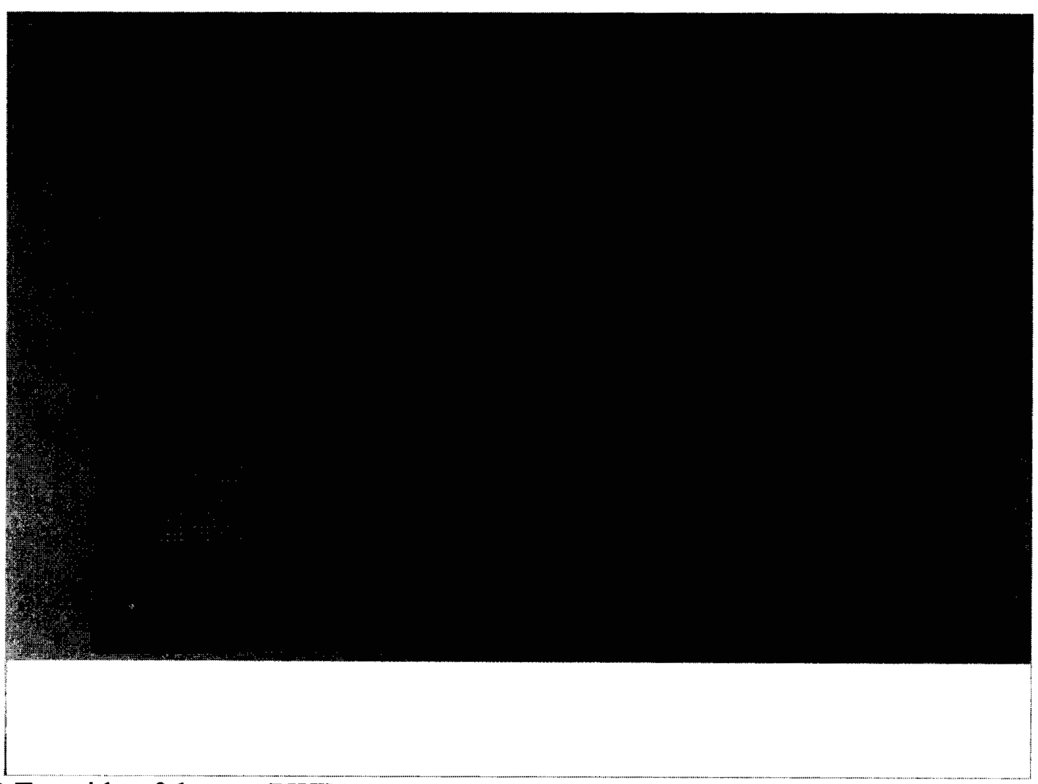

Figure 2 Top side of the test PWB

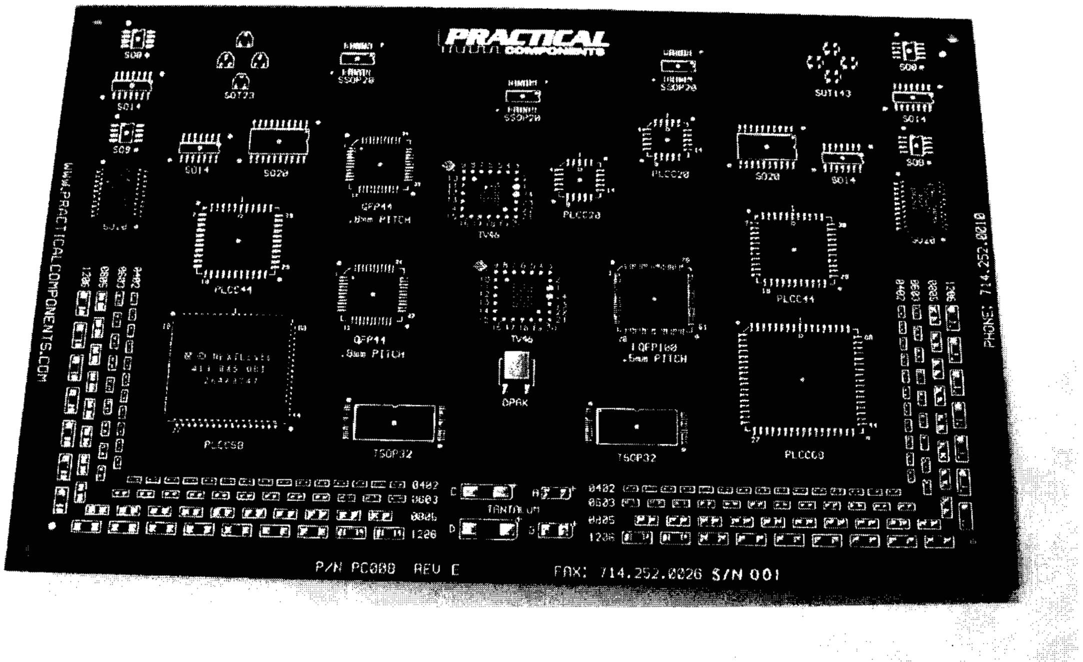

Figure 3 Bottom side of test PWB assembled with Sn95.5Ag3.8Cu0.7 (PWA001)

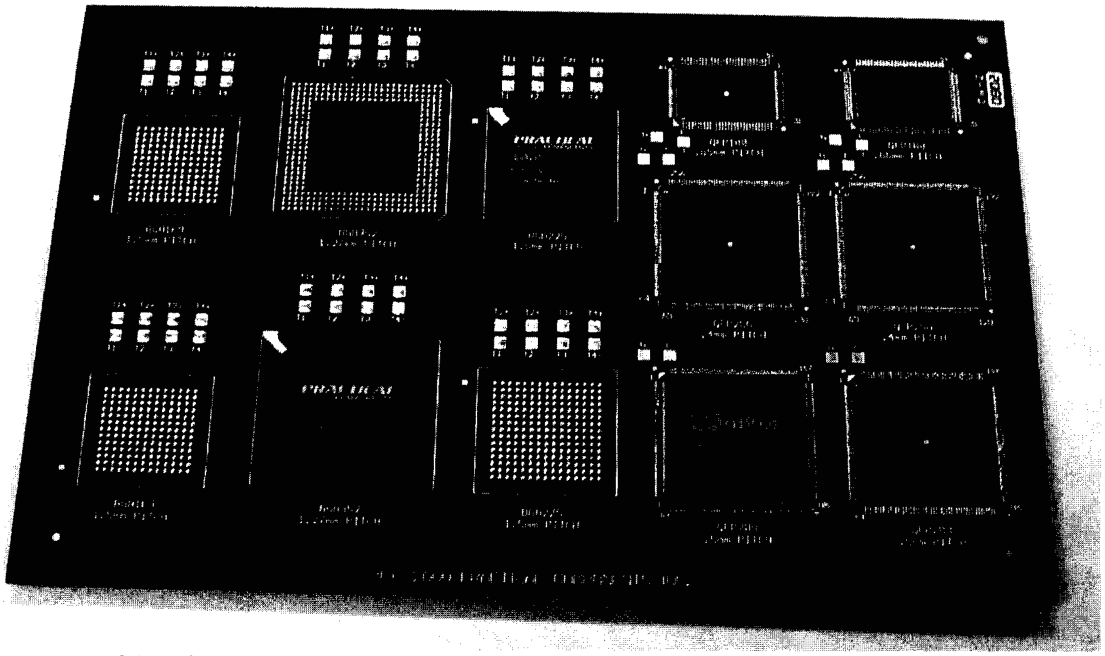

Figure 4 Top side of test PWB assembled with Sn95.5Ag3.8Cu0.7 (PWA001)

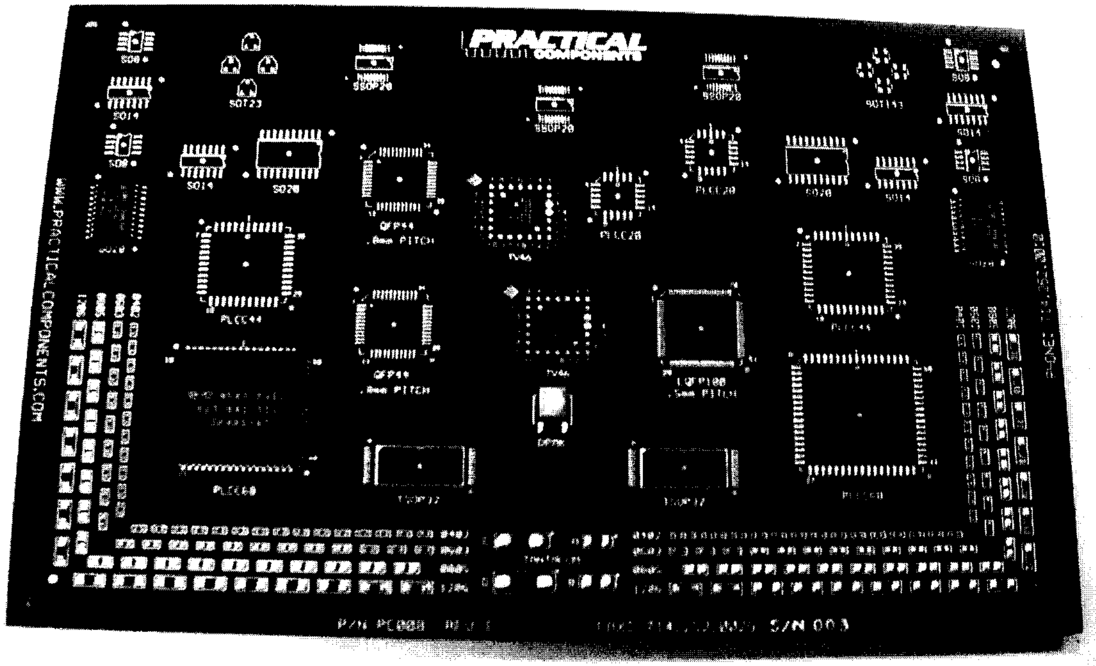

Figure 5 Bottom side of test PWB assembled with Sn96.2Ag2.5Cu0.8Sb0.5 (PWA003)

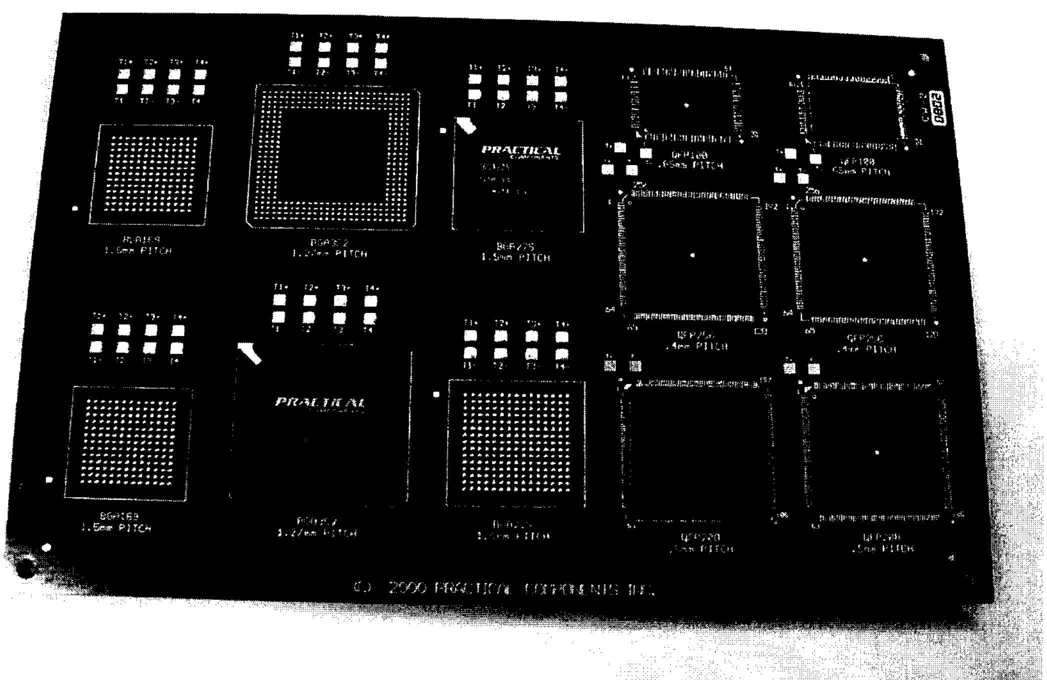

Figure 6 Top side of test PWB assembled with Sn96.2Ag2.5Cu0.8Sb0.5 (PWA003)