COLUMN GRID ARRAY REWORK FOR HIGH RELIABILITY

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I. ABSTRACT

Due to requirements for reduced size and weight, use of grid array packages in space applications has become common place. To meet the requirement of high reliability and high number of I/Os, ceramic column grid array packages (CCGA) were selected for major electronic components used in next MARS Rover mission (specifically high density Field Programmable Gate Arrays).

The probability of removal and replacement of these devices on the actual flight printed wiring board assemblies is deemed to be very high because of last minute discoveries in final test which will dictate changes in the firmware. The questions and challenges presented to the manufacturing organizations engaged in the production of high reliability electronic assemblies are, "Is the reliability of the PWBA adversely affected by rework (removal and replacement) of the CGA package?" and "How many times can we rework the same board without destroying a pad or degrading the lifetime of the assembly?"

To answer these questions, the most complex printed wiring board assembly used by the project was chosen to be used as the test vehicle, the PWB was modified to provide a "daisy chain" pattern, and a number of bare PWB's were acquired to this modified design. Non-functional 624 pin CGA packages with internal "daisy chained" matching the pattern on the PWB were procured. The combination of the modified PWB and the daisy chained packages enables continuity measurements of every soldered contact during subsequent testing and thermal cycling. Several test vehicles boards were assembled, reworked and then thermal cycled to assess the reliability of the solder joints and board material including pads and traces near the CGA.

The details of rework process and results of thermal cycling are presented in this paper.

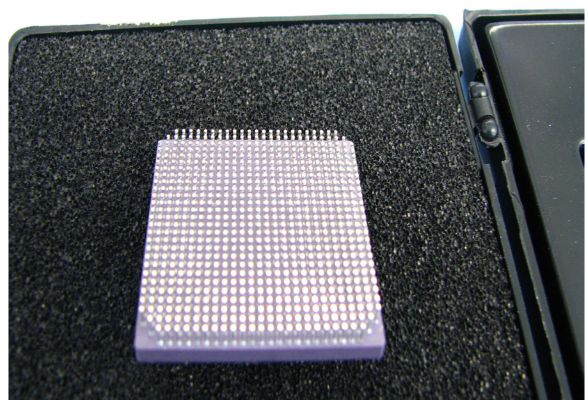
II. INTRODUCTION

As electronic devices have become increasingly complex, the number of required interconnections has far exceeded the reasonable limits for leaded packages. Quad Ceramic flat packs with 20 mil and 16 mil pitch leads are quickly becoming a thing of the past because of the limits of interconnections available (typically 256). Field Programmable Gate Arrays and other complex electronic components have, by necessity, been migrated to grid array packages to provide 600 to 1200 interconnection points in a reasonable sized package.

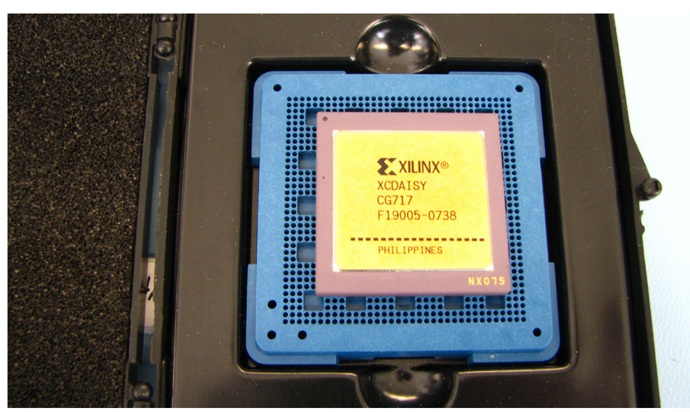
This trend has produced some difficulties for those of us involved in the production of ultra high reliability Electronics used in such applications as encountered in missions to other planets. Ball Grid Array (BGA) packages came along to conquer the interconnection problem but caused a stir in the hearts of Quality Assurance organizations throughout the space business. Their cry was that they could no longer examine the solder joints for shiny surfaces and other attributes deemed necessary in the manufacture of leaded component printed wiring board assemblies. Of course tight soldering process control along with X-ray examination became the answer to these concerns.

As BGA's grew in physical size and we were faced with longer missions on the surface of Mars with huge temperature swings from day to night, the threat to failure of solder joints due to CTE mismatches and inadequate solder joint compliance pushed us into using Column Grid Array (CGA) packaging. Figure 1 shows a photo of a 717 column package.

CGA's have the advantage of providing much greater compliance to the stresses caused by CTE mismatches than the BGA predecessors. Solder joints along the perimeter of the packages can be inspected providing some indication of the quality of the joints throughout the package. These two characteristics of the CGA give us all a sense of comfort that the mission will not fail prematurely due to solder joint failures.



CGA Bottom



CGA Top

Figure 1 717 Pin CGA Package in Protective Carrier

Cast and wire columns: Schematic of the cross-section of two types of column materials. See Figure 2.

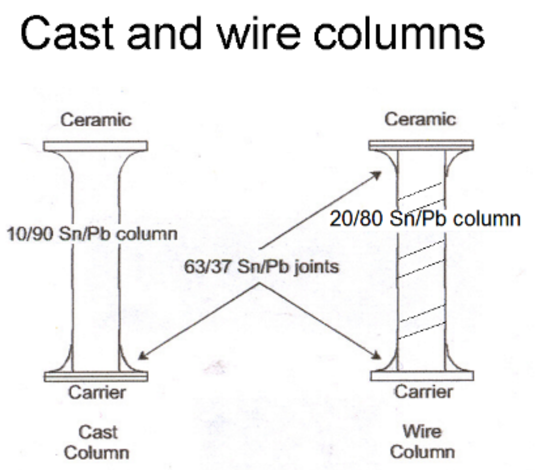


Figure 2

Cross-section of 90/10 and 80/20 Column after assembly: Optical photographs of the two types of CCGA columns that is available in the commercial market. This paper deals only with 80/20 column with the helix copper strip. See Figure 3.

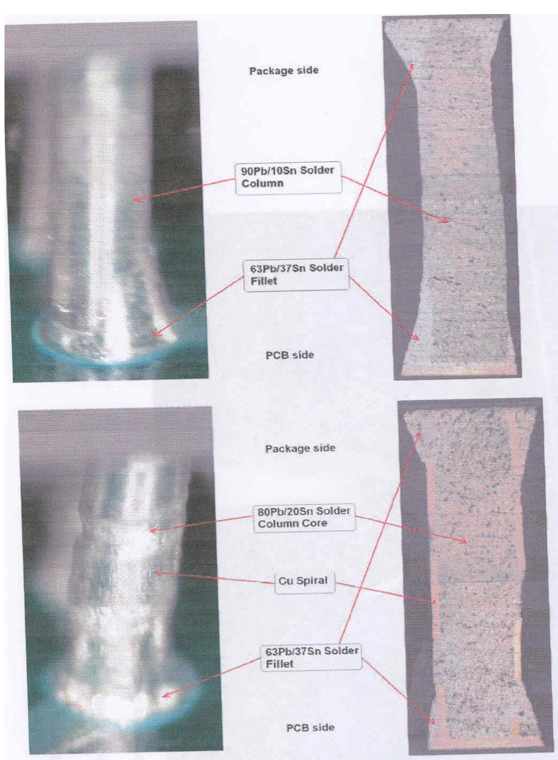


Figure 3

The questions and challenges presented to the manufacturing organizations engaged in the production of high reliability electronic assemblies are, "Is the reliability of the PWBA adversely affected by rework (removal and replacement) of the CGA package?" & "How many times can we rework the same board without destroying a pad or degrading the lifetime of the assembly?"

The Jet Propulsion Laboratory's Electronic Fabrication and the associated Quality Assurance organizations, under direction of the project, commenced an empirical study to provide the answers.

III. APPROACH

To demonstrate to a high level of confidence that the rework process would produce a flyable reworked board, it was determined that 6 boards would have to be reworked and then successfully survive accelerated thermal cycling equal to 3 times the expected mission life. This translated into 365 thermal cycles, each cycle spanning 2 hours in duration ranging from -55 to +100ºC. Qualification of the CCGA was expedited by accelerating the thermal cycle test stated in NASA Handbook by increasing the temperature range. Figure 4 shows the daily maximum and minimum temperatures actually measured for 925 Martian days (sols) by the Mars Exploration Rovers For the expected mission life of this next mission of two earth years the following characteristics of the thermal cycling tests were derived:

Thermal Cycles: 365 Cycles (for 3x life)
Delta T (ΔT) per NASA Thermal Cycle (-55ºC to 100ºC): 155°C
Dwell Time at Temperature:
~15 minutes after thermal equilibrium is reached.
Max Temperature Ramp Rate: ≤5°C/minute

Acceptance Criteria after Thermal Cycles:

- The CCGA assemblies shall be subjected to the qualification test cycle described above and the CCGA solder joints shall be inspected after 1x, 2x, and 3x life thermal cycles completion.
- After 1x life cycles; there shall be minimum signs of solder joint degradation.
- After 3x life cycles, some minor cracking, solder feature change, and solder shedding are allowed. QA will assess the solder joint integrity.

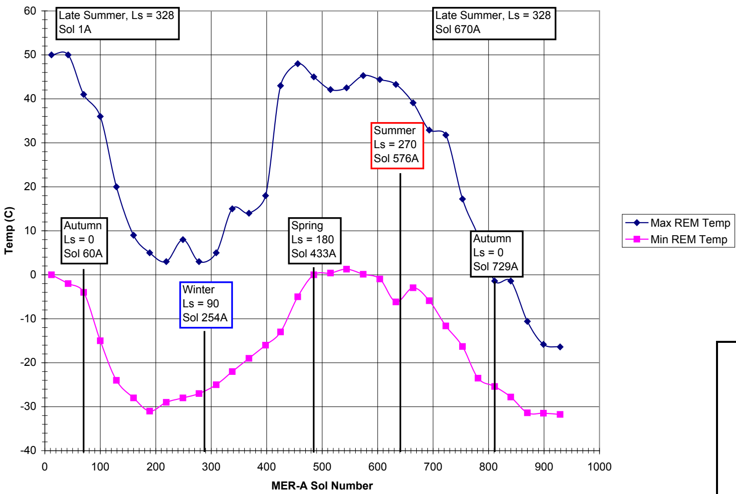


Figure 4

IV. PROGRAM PLAN

The electronic suite designed for the Mars Mission employs Field Programmable Gate Arrays packaged as 624 pin column grid arrays. The probability of removal and replacement of these devices on the actual flight printed wiring board assemblies is deemed to be very high because of last minute discoveries in final test which will dictate changes in the firmware.

Recognizing this fact of life, an experimental program was instituted many months before the actual need. This initial study used simple two-sided PWB's with no parts on the board other than the CGA. It became apparent that this study was necessary but not sufficient to thoroughly convince us of the competency of manufacturing to accomplish this in the "heat of battle". The test samples were simple two sided PWB's with no other components mounted on them while the flight assemblies are complete assemblies on 16 layer 6U size PWB's with tens of thousand of dollars worth of other space qualified parts and value added labor. Destroying one of these assemblies because of a pad being lifted during rework would be disastrous to the project.

It was decided that a test program was required to be devised which would more closely represent the real conditions expected to be encountered to raise our confidence level. The complexity parameters were those affecting the difficulty of rework. The thermal mass was a major deciding point. The thought was that the more heat energy that had to be applied to the board to reflow the solder the more the danger of collateral damage occurring during rework. Proximity of surrounding parts was another factor considered because of possible damage to those very expensive adjacent parts.

The design files of the one of the flight boards were changed only in the area of the CGA. (All ground and power planes were unaffected as were the signal layers with the exception that the CGA pads were wired in a "Daisy Chained" pattern to match the "Daisy Chained" arrangement of the dummy CGA packages. The dummy CGA's are in the same packages as the flight units with the Pb80 Sn20 columns strengthened by a copper ribbon helix as shown in Figure 3. In order to more easily localize solder joint failures, the PWB was wired to establish 5 strings with each wired to an output connector. The strings were, in general, arranged in geographical areas with the perimeter pins forming a chain, the internal center forming another and so on. Figures 5 and 6 shows bottom and top sides of the assembled board.

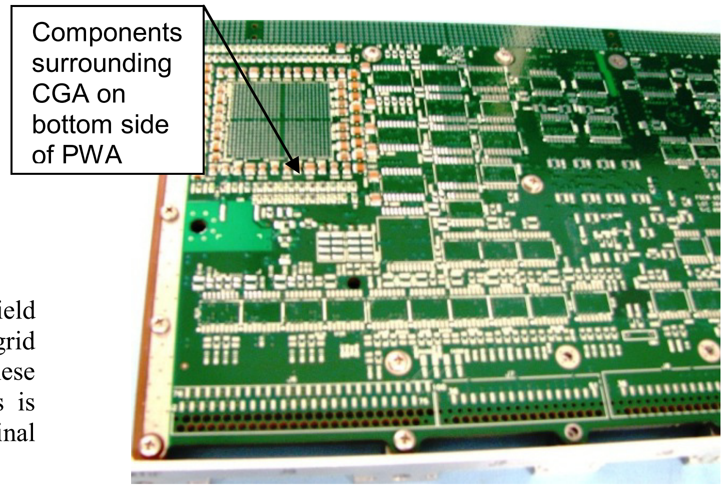


Figure 5 - Sample Test Board Bottom Side

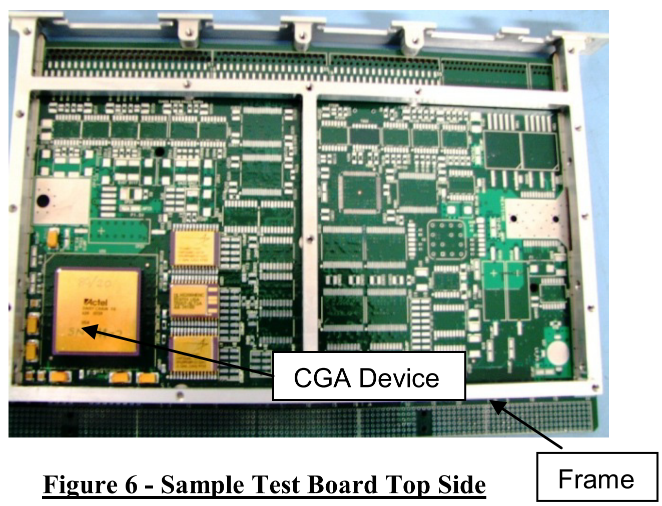


Figure 6 - Sample Test Board Top Side

V. THERMAL MEASUREMENTS ON BOARDS

A series of tests were performed to determine temperatures that other components on the boards experience during the rework cycle. Thermocouples were attached to sample boards and the rework cycle initiated. The results of these tests are detailed below.

Thermal Measurements

Since the assembly consisted of 0.125 inch thick board with several heavy ground and power planes the thermal profile was conducted in series of steps as recommended by the manufacturers. The steps are a) Preheat the nozzle b) Preheat the assembly c) Soak. the assembly and d) Heat the assembly to achieve final reflow
The maximum temperatures reached during the process are shown in the table 1. The parts on the top surface of the board all reached the temperatures to near 210 degrees C which would reflow the solder joints (183 degrees C is the reflow temperature). The underside of the PWB directly under the CGA reached 169 degrees C which is well under reflow temperature of the assemblies.

Figure 7 depicts the graphical representation of thermal profile.

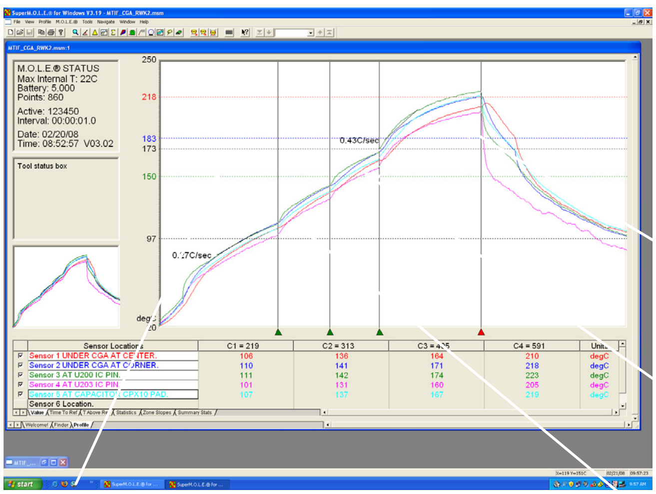


Figure 7 - Graphical representation of thermal profile

Table 1

Thermal Couple Location	**Maximum Temperature Reached ºC**
TC1 Under CGA Center	210
TC2 Under CGA Corner	218
TC3 U200 Pad	223
TC4 U203 Pad	205
TC5 CPX10 Pad	219

Another set of measurements were taken with thermocouples located at different component sites. Table 2 provides the results of the tests. Figure 8 shows the profile graphs.
Again, the parts on the top surface of the board all reached the temperatures to near 210 degrees C with the exception of the underside of the PWB directly under the CGA reaching 169 degrees C which is well under reflow temperature of the assemblies

Table2

Thermo Couple Locations	Maximum Temperature Reached in ºC
TC1 Under CGA Center	207
TC2 Under CGA at corner	206
TC3 on C11 Pad	210
TC4 on RT101 Pad	209
TC5 on bottom side of PWA under CGA	169

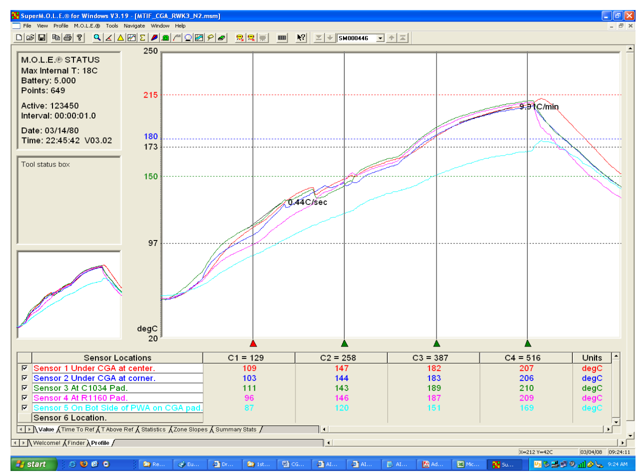


Figure 8 Graphical representation of thermal profile for Second Series of Temperature Tests

A question came up as to the temperatures experienced by the frame and the connectors mounted to the frame of the PWA slice during rework of the CGA package. Figures 9, 10, and 11 and tables underneath each provide the temperatures of the various locations on the frame and the connectors.

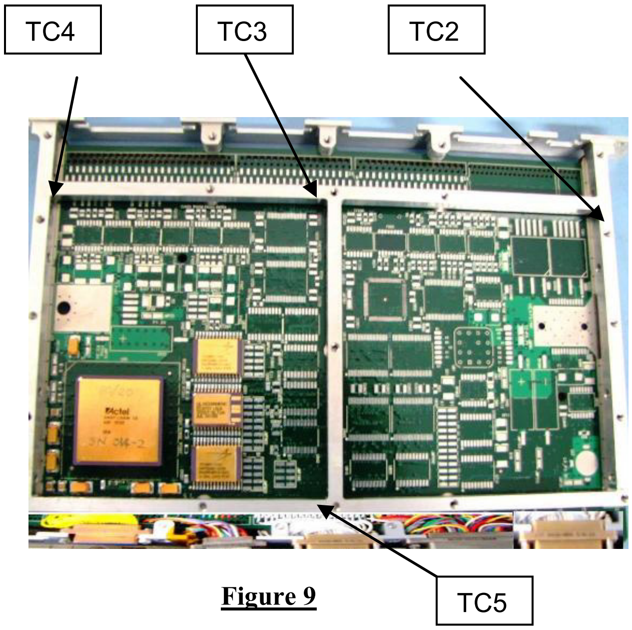


Figure 9

Thermo Couple Locations	Maximum Temperature Reached °C
TC2	175.6
TC3	128.3
TC4	100
TC5	113.9

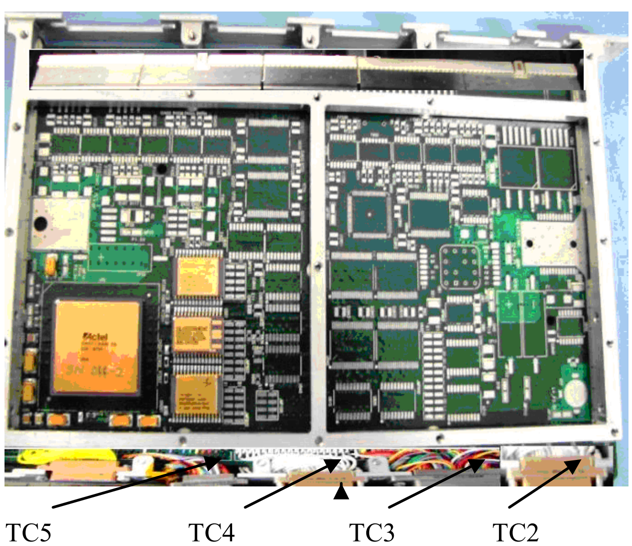


Figure 10

Thermo Couple Locations	Maximum Temperature Reached °C
TC2	113.9
TC3	122.2
TC4	116.7
TC5	116.7

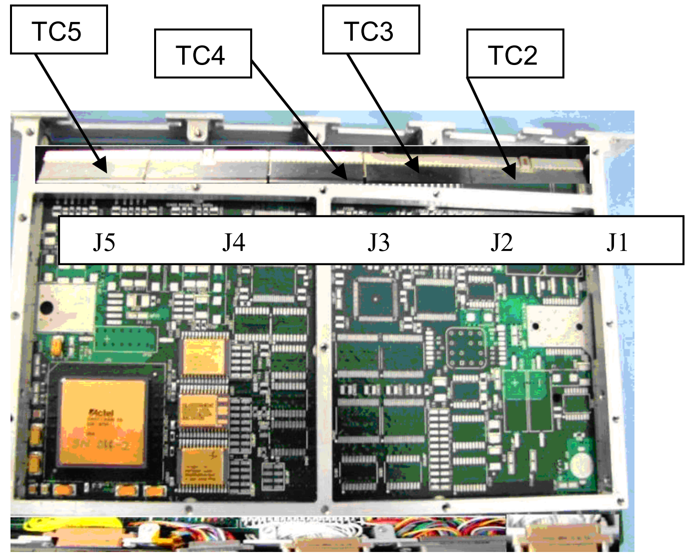


Figure 11

Thermo Couple Location	Maximum Temperature Reached °C
TC2	155
TC3	137.2
TC4	103.9
TC5	93.9

Four test PWB's were populated selectively to reduce the cost of parts sacrificed for the tests. The electronic components directly opposed to the CGA on the backside of the board were installed as were all parts within a couple of inches from the CGA. Solder paste (SN63, Pb37 with RMA flux) was applied to the entire board by stencil printing process. Parts were placed by standard pick and place techniques except for the CGA package which was placed using the precision placement capabilities of a split vision rework system. The board was then reflowed in a Vapor Phase Reflow machine. A couple of PWB assemblies were set aside to be the control samples and the others became the rework test samples.

Figures 12 and 13 Shows a series of typical solder joints obtained after the vapor phase reflow.

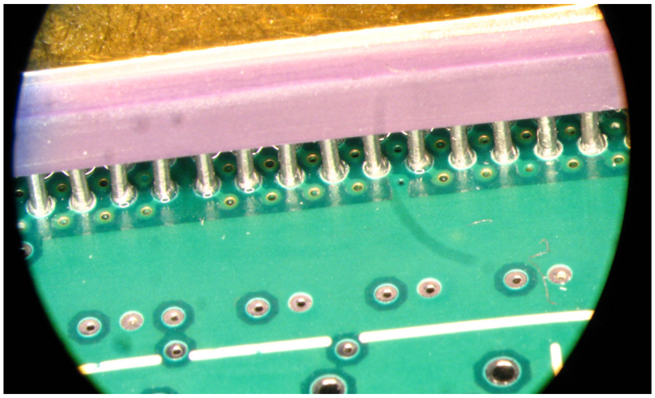


Figure 12 - CGA Columns Soldered to PWB

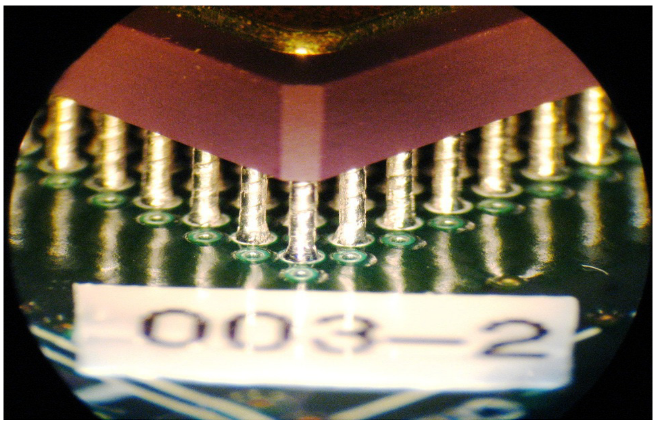


Figure 13 – Close up view of CGA Columns Soldered to PWB

VI. REMOVAL AND REPLACEMENT OF CGA USING HOT GAS REWORK SYSTEM

The Hot Gas Rework station provides a highly accurate system for the placement of Ball Grid Array (BGA) and Column Grid Array (CGA) packaged devices. .Split vision optics allows the operator to view the PWB pad area and the bottom of the part simultaneously. Micro manipulators (X, Y, and θ) provide the operator with the fine adjustments required to accurately align the part to the board. The stated accuracy is 0.0014" true position. Once the operator is satisfied that the balls or columns of the part and the pads on the PWB are aligned, the machine is commanded to lower the part onto the pasted pads with predetermined controlled force. In the case of removal and replacement of the CGA, the CGA pads on the PWB are pasted using a mini stencil and a small spatula and then reflowed by the hot nitrogen stream on the rework system.

Figure 14 shows a photo of the rework station. The rework system is equipped with top and bottom heaters and a specially designed nozzle with diffuser for CGA 624 package. Four metallic heat shields were installed over the bottom heater to minimize heat losses to ambient during the heating cycle.

VII. CONFORMAL COAT

The first experiment involved the removal and replacement of the CGA after the assembly had been conformal coated. The coating material is applied to the board by spray technique but, to protect the circuitry under the part, the material is diluted and pushed under by a stream of dry nitrogen gas. Reworking a conformal coated board was considered to be the worst rework case that is expected to be encountered in the project life. This expectation was proven to be true.

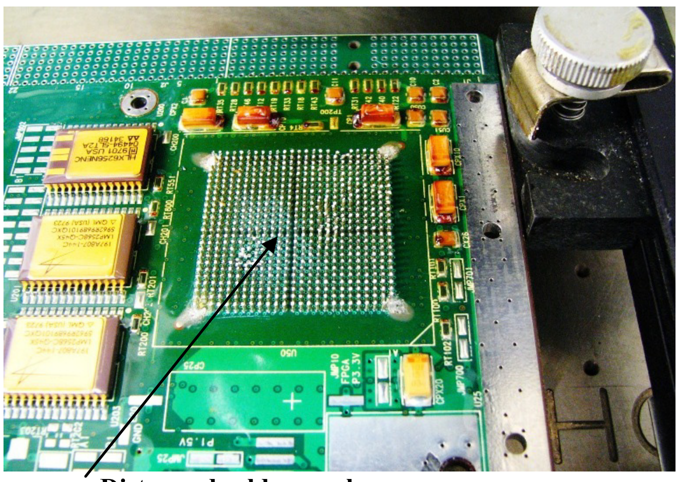
Removal of the original CGA package from the conformal coated assembly was done using the Hot Gas Rework system. The removal process resulted in all of the columns separating from the ceramic package and remaining soldered to the printed wiring board pads. See Figures 15 and 16. Figure 16 shows columns under UV light reflecting the conformal coat. Each column is attached to the bottom of the ceramic package with Sn63 solder and reflows at the same time as the Sn63 on the pads. The coating adds an adhesive quality to the PWB and, hence, the columns have a greater tendency to stick to the PWB. Removal of the columns and cleaning of the pads of conformal coating residue required 8 full hours of work by a highly skilled technician using solder wick and cleaning solvents. The pad area was very noticeably distressed by the intensive cleaning action. See Figure 15. Further the solder mask between the pad and the associated via was destroyed at three locations. See figure 17. This damage, if not repaired, will result in the solder that is melted during reflow running down the via and, thereby, starving the solder joint between the column and the pad creating a questionable connection. The solder mask was repaired by the application of a tiny ribbon of epoxy isolating the pad from the via preventing the solder from following the trace to the via. From this experience it was recognized that conformal coating of the CGA should be delayed as late in the testing as possible to avoid the necessity of reworking conformal coated packages and to avoid the associated risk to the assembly. The CGA was replaced using the rework system in following sequence.

- Deposit Sn 63 solder paste on to the pads, using mini stencil.
- Place the device using split vision rework system
- Reflow the solder using the same rework system.

The daisy chains were all determined to be 100% connected by resistance measurements.

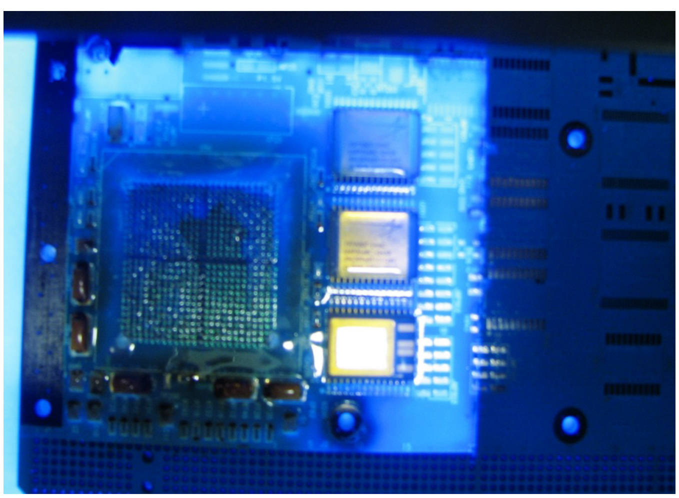
Figures 18 and 19 shows solder joints formed during the rework process whereas figures 20 and 21 shows the X-Ray views of CGA solder joints. The Joints as viewed in X-Ray image appear to be uniform and without any apparent anomalies.

<u>Figure 14 - Split Vision Rework Station with heat shields installed</u>

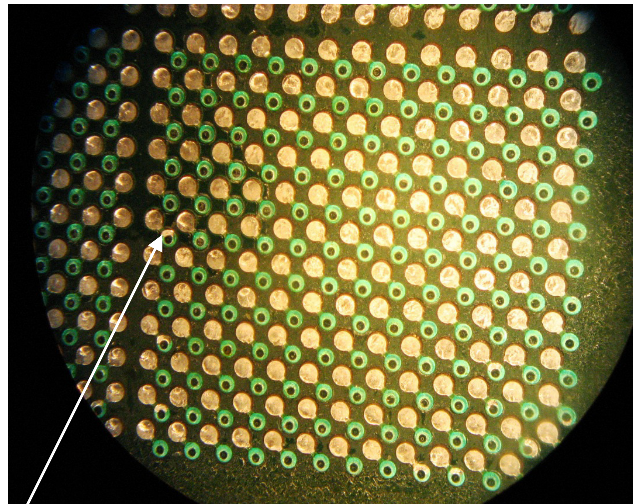


Distressed solder mask

<u>Figure 15 - Most Columns remain on PWB after part</u> removal



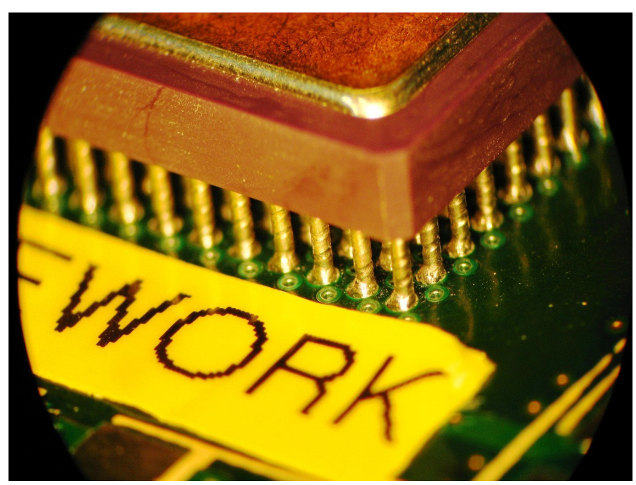
<u>Figure 16- Conformal Coated Board as viewed under UV light</u>



<u>Figure 17 - Conformal Coated Board pads after removal and Clean-up of Columns</u>

Solder mask damage

<u>Figure 18 - Solder joint generated by rework process</u>



<u>Figure 19 - Close up view of Solder joint generated by rework process</u>

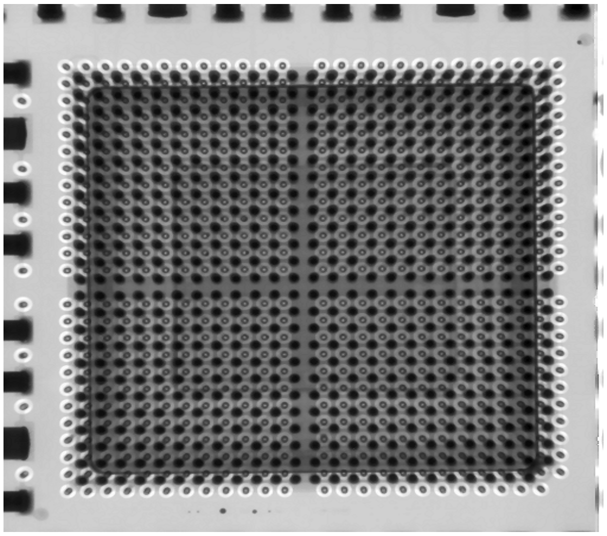


Figure 20 - X-Ray view of solder joints after rework

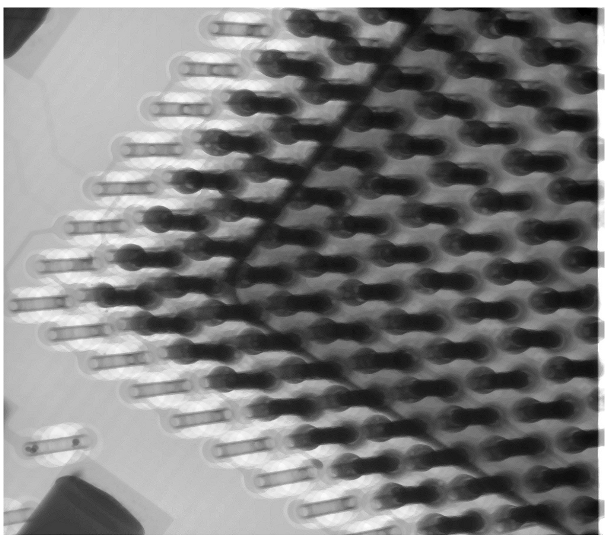


Figure 21 - Tilted X-Ray view of solder joints after rework

VIII. NON-COATED BOARD

Another test sample was prepared and soldered on the vapor phase soldering machine, but was not conformal coated. The CGA was removed using the rework station. The clean-up of the pads took the same technician less than 2 hours to complete. The pad area after rework looked pristine. See Figure 22. There was no damage to the pads or to the solder mask. The new CGA package was placed and soldered using the rework system. The daisy chains were all determined to be 100% connected by the resistance measurements.

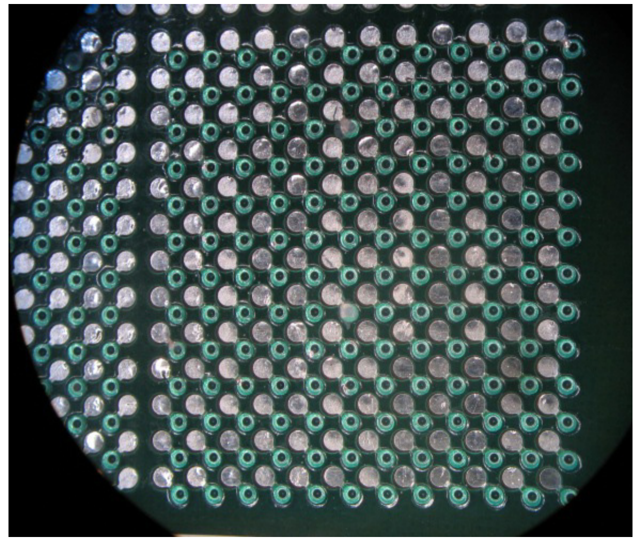


Figure 22 - Non Conformal Coated Board pads after removal of CGA and Clean-up of Columns

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In Figure 23, shown are the Close up view of Solder joints generated by rework process.

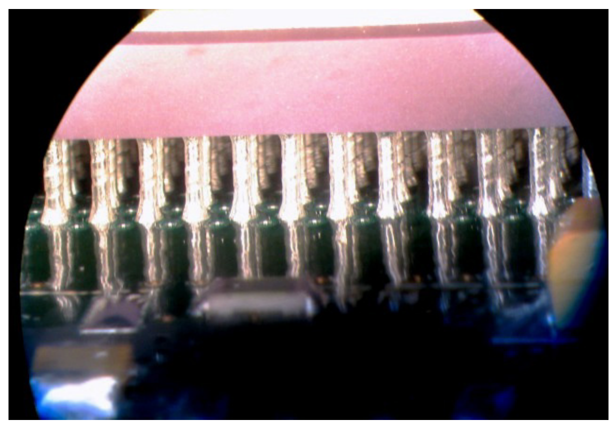

Figure 23

IX **THERMAL CYCLING TESTING**

First Test Series

All four test samples were placed in a temperature cycling chamber. The four included the 2 test control samples which had undergone no rework, the reworked conformal coated board, and the reworked board that had not been coated. The chamber was set for 122 minute duration cycles from -55ºC. to +100ºC.

Analysis had been done which indicated that 121 of these cycles is equivalent to the temperature cycles that the electronics will experience in one expected lifetime of the mission. It is the policy published in the Flight Practices to qualify processes by testing to 3 times life or in this case 363 cycles. At each 121 cycle interval the resistance of the 5 chains on each of the 4 printed wiring board assemblies was measured. Test Results showed that no failures of solder joints were detected throughout the three lifetimes of temperature cycling tests. The resistance measurements taken at key points indicated that changes were very small and within measurement errors.

S*econd Test Series*

Eight additional boards were built up, reworked, and thermally cycled. One assembly was also reworked once and then the CGA package was staked on the four corners with adhesive in the same manner as all of the flight devices. The corner staked configuration was tested to determine if there is any affect of the staking on the overall reliability. Two of the boards were reworked twice (i.e. an original part was soldered by vapor phase, replaced once with the rework system, and then second time removed and replaced by the rework system.

The thermal cycling of total eight boards was done using continuous monitoring instrumentation as well as resistance measurements taken at regular intervals by manual techniques. Because of demanding flight hardware builds during this period, the rework on the boards was stretched over a few weeks and the start of thermal cycling was, therefore, staggered. The number of cycles varies over the suite of boards. Four boards have undergone an equivalent of 8 lifetimes (968 cycles) without failures. These are the boards with one rework. The one rework board with the corner staked part (002-1) has undergone 592 cycles. The two boards with two rework cycles (003-1,002-2) have been cycled 447 cycles which is well over the 3 lifetime equivalent. No failures or anomalies have occurred on these 7 samples

A failure of S/N 013-2 was initially detected after 169 Cycles by the continuous monitoring instrumentation. The failure was in chain 1 of the five chains instrumented on each CGA. At 207 cycles manual resistance measurements showed that the circuit had a resistance of 118 ohms. As the measurements were being taken, it was noticed that the resistance of this chain reduced to 9 ohms indicating that the high resistance circuit had sensitivity to movement. (This is consistent with a cracked solder joint). The chain resistance was 2.89 ohms at the beginning of the test sequence which is representative of all chain 1's on all samples.

The cycling test was continued primarily to determine if the other chains would fail which would indicate a soldering error on the entire part.

The test was terminated after 328 cycles with the other chains intact. The measured resistance of the failed string at that time was 64K ohms in contrast to the 3 ohms that is the normal value. Through resistance measurements, the column associated with pin E22 was suspected. Microsectioning was performed by Section 514 Failure Analysis Lab. The photo in Figure 28 labeled "Suspected Column" shows the column E22. The solder fillets appear to be good and are similar to columns adjacent to it. SEM analysis was also performed and no cracks or any anomalies were detected. In fact all solder joints that were inspected were of high quality. The second photo (Figure 29) shows the via associated with the column E22. All vias inspected on the board and on the test coupon provided with the board are intact and are of high quality. No definitive cause of the failure was found, but all evidence would lead one to believe that the solder process was not at fault. The early failure (169 cycles), when all other boards went through many more cycles with no failures, indicates an infant mortality of the part.

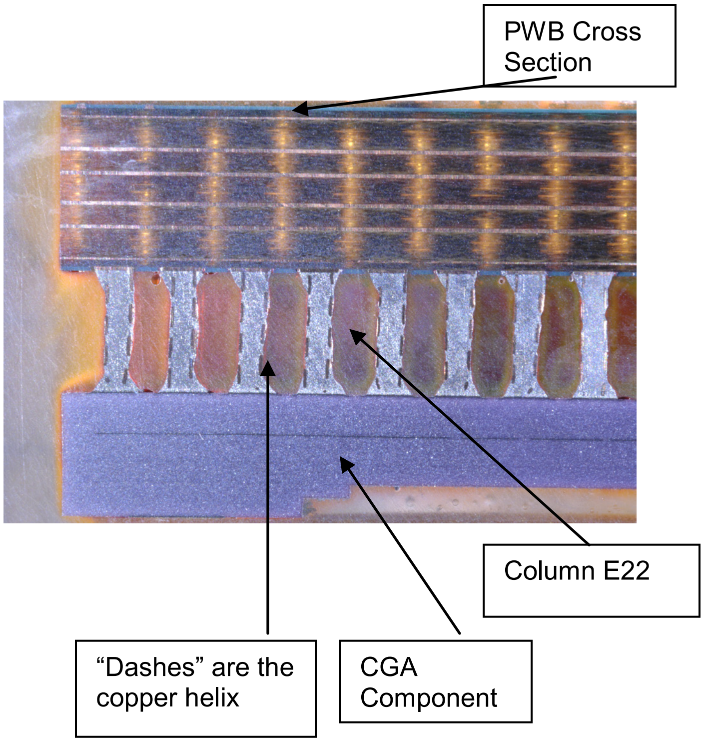

Figure 24 - Suspected Column

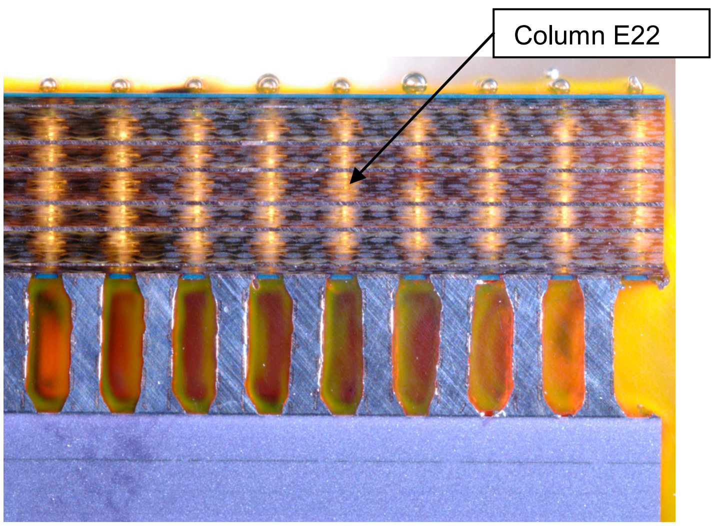

Figure 25 - Suspected Via

X. TEST EQUIPMENT

The thermal cycling test setup is shown in Figure 30. It consists of a Thermotron temperature chamber, a computer, and a rack containing the instrumentation modules. The Computer controls the chamber, monitors the instrumentation modules, and logs the occurrences of anomalies detected by the instrumentation modules. It runs on a version of LabView with Windows as the operating system.

The instrumentation modules are the National Instruments Model SCXI-1162. The SCXI-1162 has 32 channels of optically-isolated digital inputs. There are 24 such modules in the rack providing up to 768 channels of which only a small fraction was used in this test. This module was selected because of its inherent immunity to common mode noise such as large switching spikes generated by the thermal chamber.

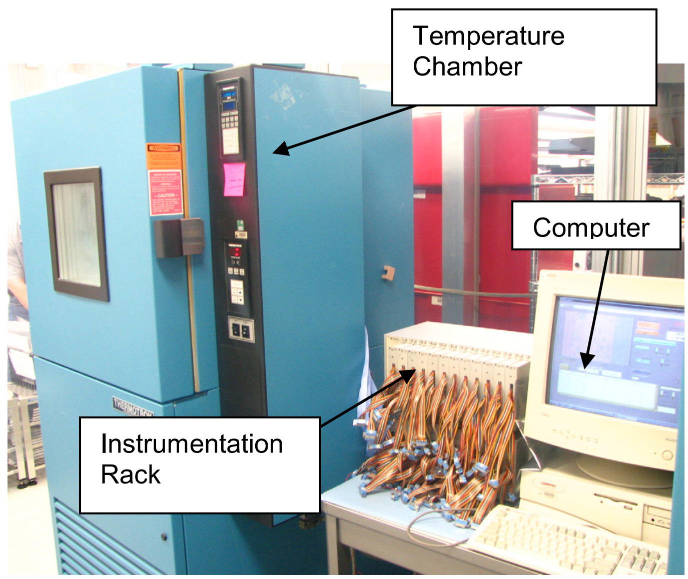

Figure 26 - Thermal Cycling Test Setup

XI. CONCLUSION

The removal and replacement of Column Grid Array packaged parts from densely populated printed wiring board assemblies can be done successfully, but it requires care in the selection of reflow profiles and process procedures. The reliability of the solder joints of the reworked assemblies is excellent and far exceeds the 3 times mission lifetime as required by the NASA specifications. The major danger in the process appears to be in the solder mask being overstressed and damaged in the cleanup after the removal of the defective part. This danger is specially exacerbated by the presence of conformal coatings under the part. Pad lifting was not experienced except for one incident that was easily repaired because only the corner of the pad was detached from the PWB. Adjacent parts do not experience temperatures much above those normally reached during Vapor Phase reflow (Approximately 216º C). The solder joints of those parts do reach reflow temperatures and can be easily displaced with any disturbance. To err on the side of caution, it was decided to replace small discrete components within ½ inches of the CGA, and to remove expensive long lead parts within this zone before rework and replace them after rework.

XII REFERANCES

1. Ceramic Column Grid Array Assembly and Rework Guide,
2. IBM Corp.
3. NASA Handbook.

XIII. ACKNOWLEDGEMENTS:

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