National Aeronautics and Space Administration

Reliability of Carbon Core Laminate Construction in Printed Circuit Boards Utilizing Stablcor$_{TM}$

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NASA Electronic Parts and Packaging (NEPP) Program
Office of Safety and Mission Assurance

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Abstract

There is a trend continuing in the electronics industry where high reliability electronic packages are using standard epoxy glass and polyimide substrates over ceramic-based substrates. This is a result of improved fabrication accuracy and consistent raw material properties. Increased processing power is resulting in increased heat generation. Printed circuit boards are becoming very dense as a result of improved fabrication processes that allow smaller vias and smaller trace line width/spaces and pad size. This is combined with designs that have multiple internal conductive layers that routinely reach 20 to 25 layers. This increased processing power is affecting printed circuit board designs for space electronic applications. The additional heat must be conducted from a microprocessor or power device through the printed circuit board to the board frame or chassis. This has been achievable for processing devices by utilizing thick copper layers and thermal vias to transfer the resultant heat. The result of increasing the copper thickness is an increase in mass, which is an undesirable condition when the goal for space-designed electronics is a smaller and lighter electronic package.

Recent technology development in raw materials has given printed circuit boards increased heat transfer capabilities for a given mass over copper. This is achieved by using carbon fiber within a printed circuit board cross-section during the lamination process. The carbon fiber, which resembles a fabric weave, is embedded in a resin and sandwiched between copper foil; it is referred to in the electronics industry as carbon core laminate or CCL. This task was designed to utilize CCL for improved heat transfer and improved solder interconnection reliability. The title of this task was stated as printed circuit board reliability, but the actual experiment focused on heat transfer performance and solder joint interconnection reliability with respect to ball grid arrays and column grid arrays.

1. Introduction

The development of improved manufacturing processes for fabricating copper foil and CCL raw material stock has allowed for the introduction of this technology to industry by multiple printed circuit board suppliers. The domestic and international printed circuit board market is seeing an increasing number of licensed users of CCL with the trademarked name of Stablcor, with intellectual property held by Stablcor Inc.

The primary objective of this applied research was to establish the heat dissipating performance of printed circuit boards that are constructed with CCL. The secondary objective was to improve the solder joint interconnection reliability of column grid arrays (CGAs) and ball grid arrays (BGAs) on printed circuit boards with CCL. The tertiary objective was to evaluate the reliability of the printed circuit boards constructed with CCL during thermal cycling. The testing performed was focused on the ability of the CCL construction to enhance the flow of heat from a device source and distribute that heat more efficiently than a standard copper/polyimide-based solution. The principal benefit for space-related electronics would include the ability to cool electronics more efficiently without increasing mass.

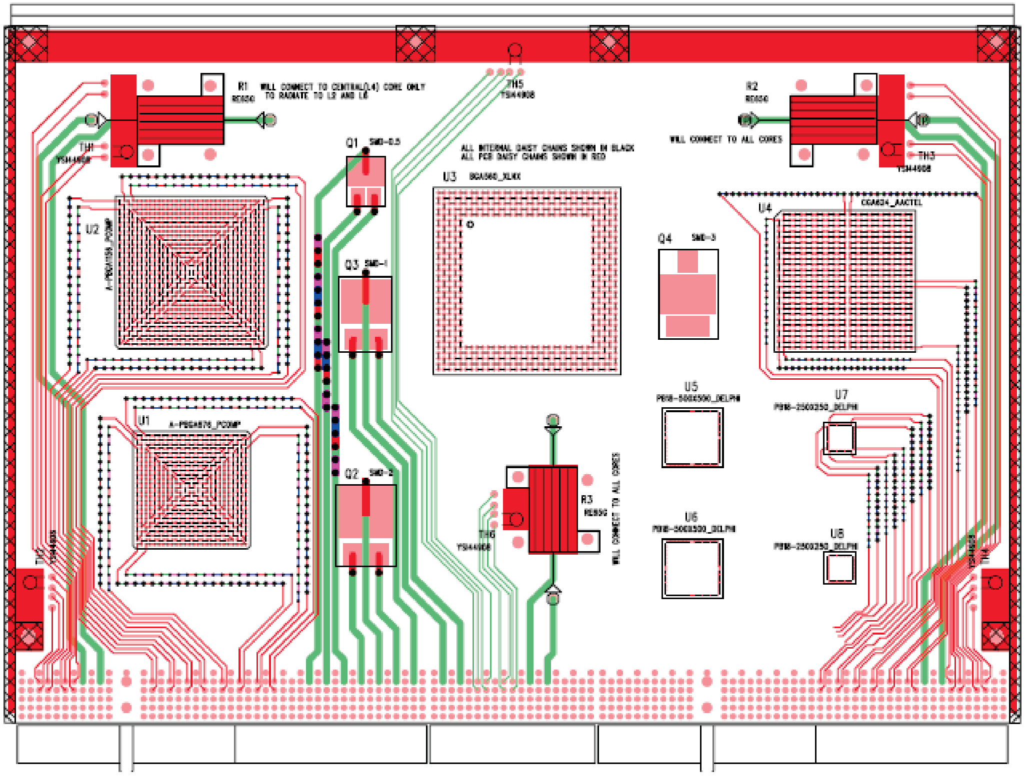

Figure 1. Drawing of the Top Side of Test Printed Circuit Board with Three 10-Watt Resistors R1, R2 and R3

2. Test Vehicle: Printed Circuit Board Design

The test vehicles for this experiment were designed to represent a very common printed circuit board size frequently used in space electronics. Carbon core laminate (CCL) used in printed circuit board construction was incorporated as heat transfer layers that could function as an electrical ground plane as well. Typical printed circuit boards are composed of prepreg and copper foil with the copper foil laminated to prepreg on both sides. When fabricating a structure with CCL, the material was incorporated into the printed circuit board construction pre-laminated between copper foil. The lamination layer is essentially copper on both sides with a carbon fiber weave and epoxy resin in the middle. There can be a single layer of CCL or multiple layers of CCL in a printed circuit board, depending on board thickness requirements. The CCL needs to be symmetrically stacked in the board cross-section for optimal flatness results.

There were three different types of printed circuit boards tested. They were identical in size, length, width, and thickness. The boards were constructed to a Compact PCI Bus standard card size of (6U) 233.35 mm by 160 mm. The board thickness was 2 mm. The first type was of standard polyimide and copper inner layer construction with no CCL. Copper/prepreg/copper raw material was used as the primary heat transfer layer and is depicted in Figure 2. The second type included two layers of CCL placed symmetrically within the board cross-section. This CCL was a material type called ST-10. The third type included two layers of CCL placed symmetrically within the board construction.

This construction contained a material type called ST-325. The ST-10 and ST-325 have different heat transfer properties. The ST-10 CCL weave conducts heat at 75 W/m-K, and the ST-325 carbon core weave conducts heat at 175 W/m-K. The printed circuit board test vehicles used in this testing were fabricated with printed circuit board panels with two layers of CCL. The CCL layers were incorporated near the top and bottom of the printed circuit board panel to form a sandwich construction. Refer to Figures 3 and 4 for panelized printed circuit board cross-sectional construction that depicts the material stack-up of the printed circuit boards constructed with CCL ST-10 and CCL ST-325.

The CCL should be stacked in a symmetrical fashion to ensure maximum stiffness and to avoid potential warping that may affect circuit board flatness. The test vehicles were designed to accommodate several types of testing. There is an assortment of land patterns to allow placement of CGAs, BGAs, transistors, flip chip devices, and large resistors. The test vehicles used for this experiment were populated with only resistors; the remaining board surface did not have any components during this testing. The resistors were located with sufficient space between them in order to impart heat in the portion of the board where they are located. The board design and layout is shown in Figure 1. See Figure 5 for the actual fabricated printed circuit board test vehicle with the heat-generating resistors installed. The resistors are located in the top left and right corners as well as in the board bottom center. The resistors are capable of generating 10 Watts of power each. This is enough to generate much more heat than the average printed circuit board will see during operation over different temperature environments. The board pad location for each resistor was the same size as the resistor footprint, and a thermally conductive epoxy was applied to the pad surface prior to resistor placement. The epoxy contained a glass bead filler to guarantee a uniform bond line thickness of three thousandths of an inch. The resistor was hand placed and mechanically attached with fasteners. The epoxy was then cured per the material application instruction sheet. The resistors were wired from their terminations to the printed circuit board. Traces on the top layer lead to the board edge where they were connected to 28-gauge wires that provide the voltage/current to generate heat from the power supply to large resistors.

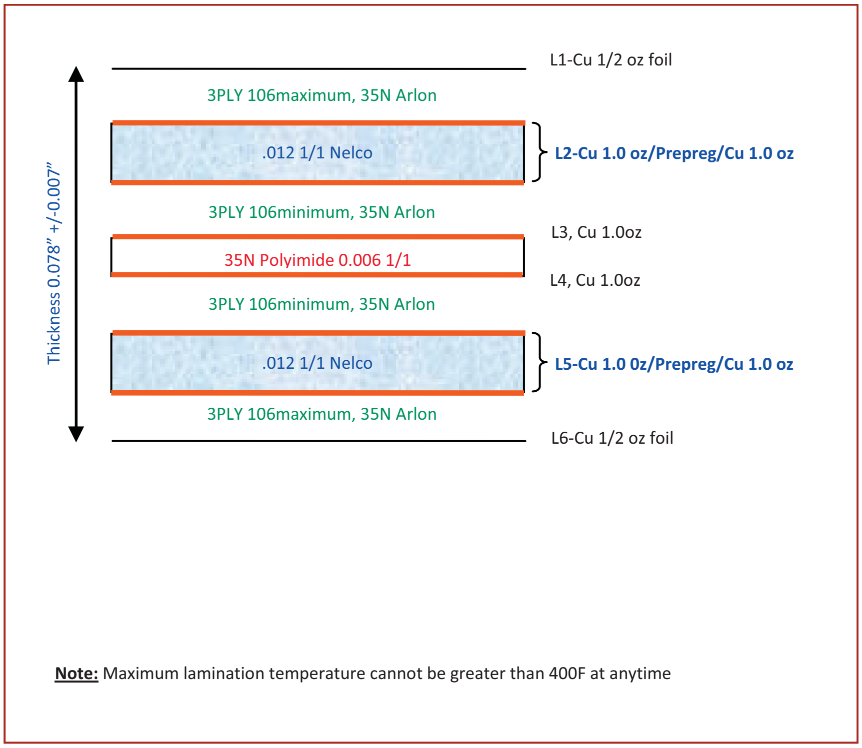

Figure 2. Printed Circuit Board Cross-Section Materials Stack-up without CCL

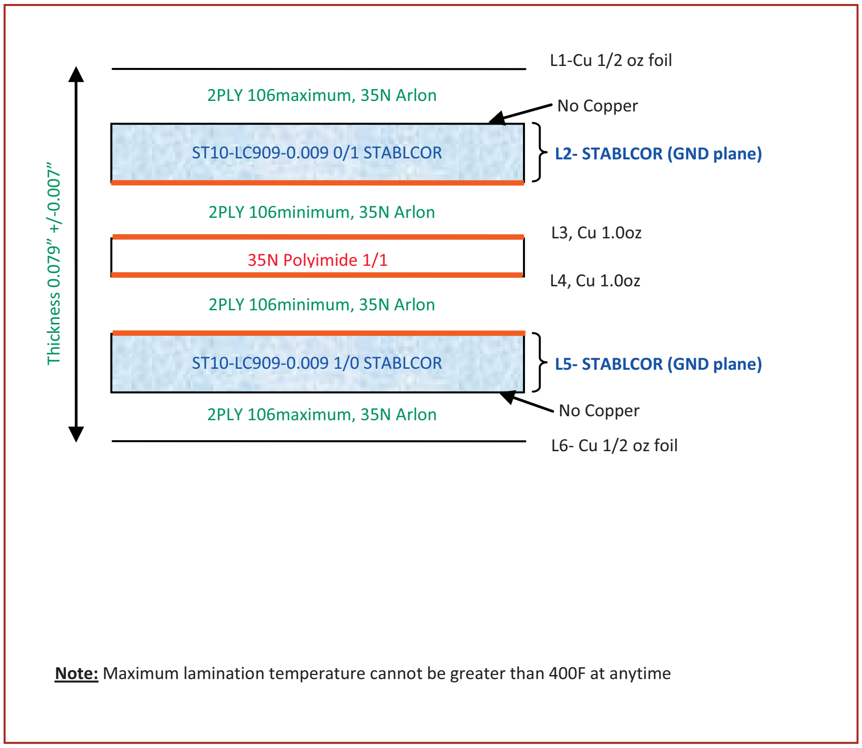

Figure 3. Printed Circuit Board Cross-Section Materials Stack-up with ST-10 CCL

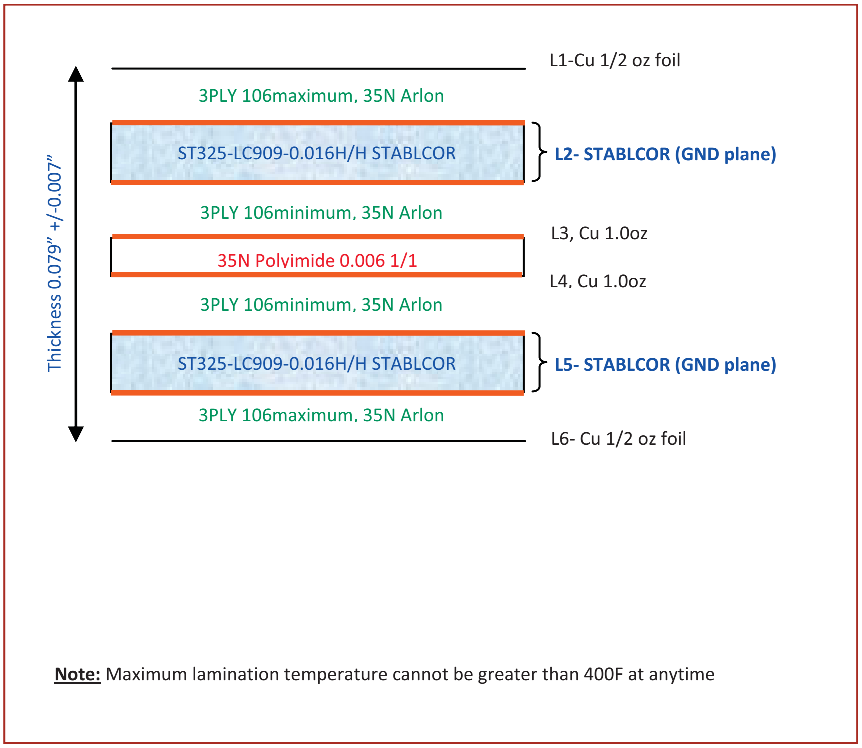

Figure 4. Printed Circuit Board Cross-Section Materials Stack-up with ST-325 CCL

3. Test Vehicle: Heat Transfer Testing

The printed circuit boards were tested individually by construction type starting with the polyimide printed circuit board without CCL. The test boards were placed in a vacuum chamber while supported on small nylon blocks. See Figure 6 for a picture of the vacuum chamber interior. Nylon insulators were chosen to minimize any heat sinking effect of the supports. The intent was to provide nonconductive heat sinking from the board to the chamber. The chamber was pumped down to 6.2 x ¯10 torr over a period of 30 minutes. Once the vacuum was stabilized, the resistors on the board were energized with a current source to produce approximately 5 Watts of power output to the resistors using an Agilent E3634A power supply. This was achieved by energizing the resistors with 7.1 volts and .71 amps of current through the 10-ohm resistors. All resistors were energized at the same time and allowed to heat up in the vacuum chamber. Infrared imaging was utilized to take an image of the board at zero time and once every minute for 30 minutes. The experiment was repeated for the test vehicle board constructed with CCL material type ST-10 and CCL material type ST-325. Again, the current power input, vacuum, and time energized were the same as the polyimide construction test vehicle board. Comparisons were made between the infrared images taken at the same time interval to better understand the rate of heat transfer. The infrared images in this report reflect the heat saturated printed circuit boards where conduction had reached a steady state and the radiation of heat would begin within the chamber. The infrared picture images taken after 30 minutes represent the data best suited for the basis of the testing conclusions. This is considered the point at which this technology's performance can be properly evaluated. Figures 7, 9 and 11 show the infrared thermal image of each printed circuit board type after the resistors were energized for 30 minutes, which is the maximum temperature achieved during testing. This is evident in the thermal profiles shown in Figures 8, 10 and 12 where the slope of the curve becomes zero. During actual testing, the duration in the vacuum chamber was 45 minutes. The slope did not change from 30 minutes to 45 minutes, indicating the temperature had reached a steady state. The result of this heat transfer testing is summarized in section 5.0.

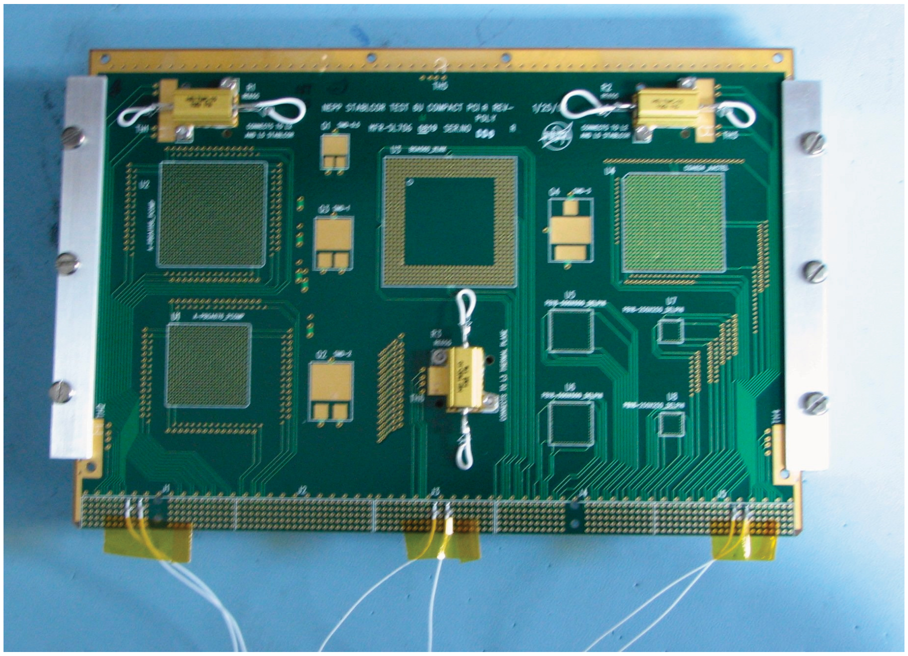

Figure 5. Printed Circuit Board with Three 10W Resistors

Figure 6. Vacuum Chamber; Amray 1830I Used for Heat Transfer Testing

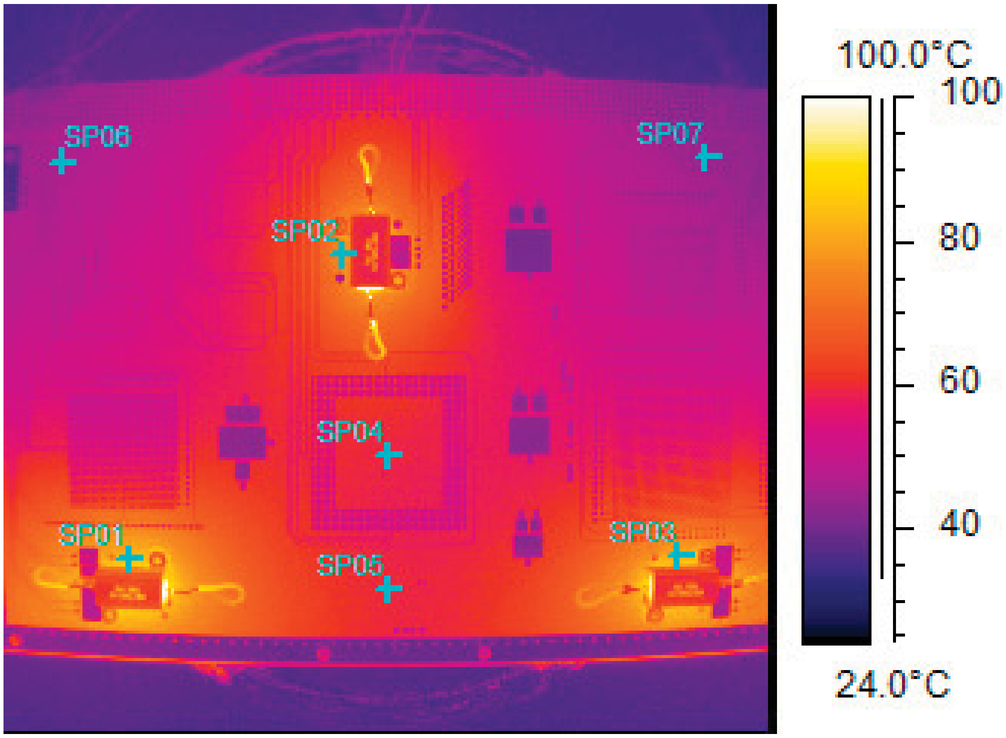

Figure 7. Infrared Image of Thermal Heat Distribution for Polyimide Construction (without CCL)

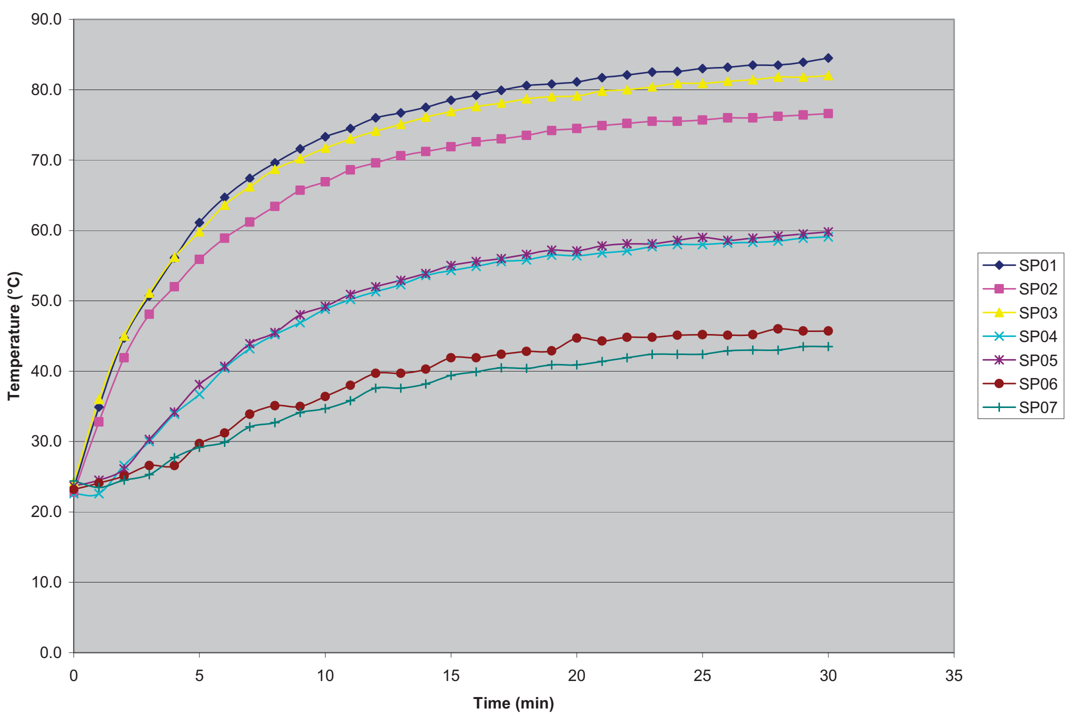

Figure 8. Temperature Profile Polyimide Construction (without CCL)

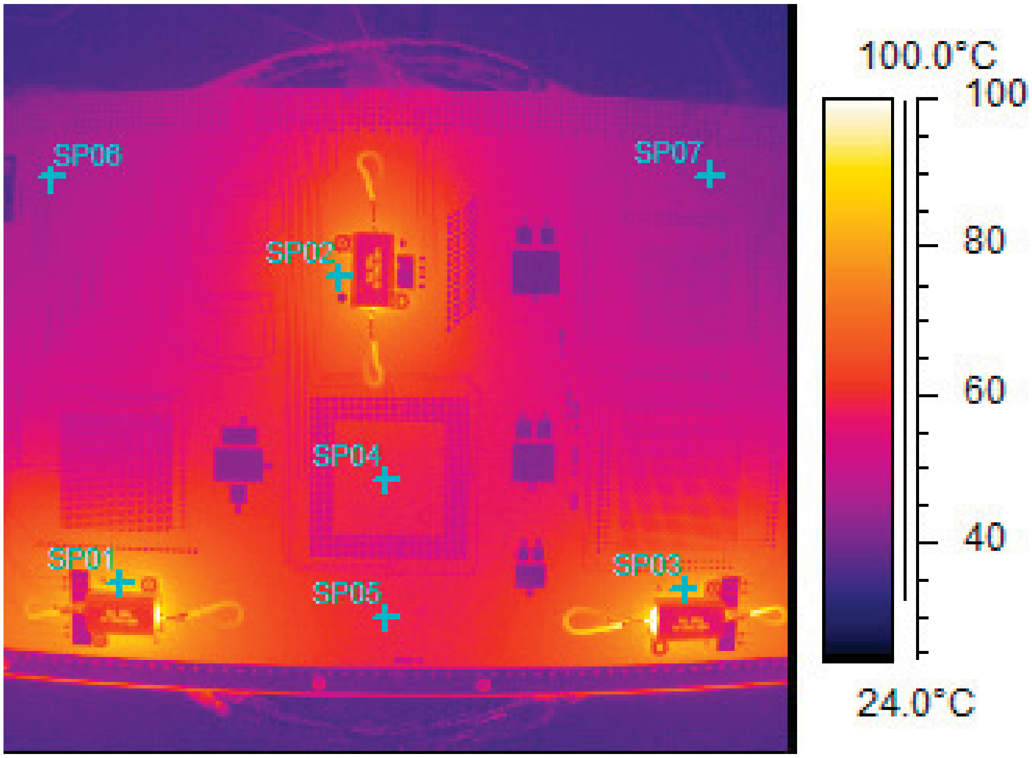

Figure 9. Infrared Image of Thermal Heat Distribution for ST-10 Construction (with CCL)

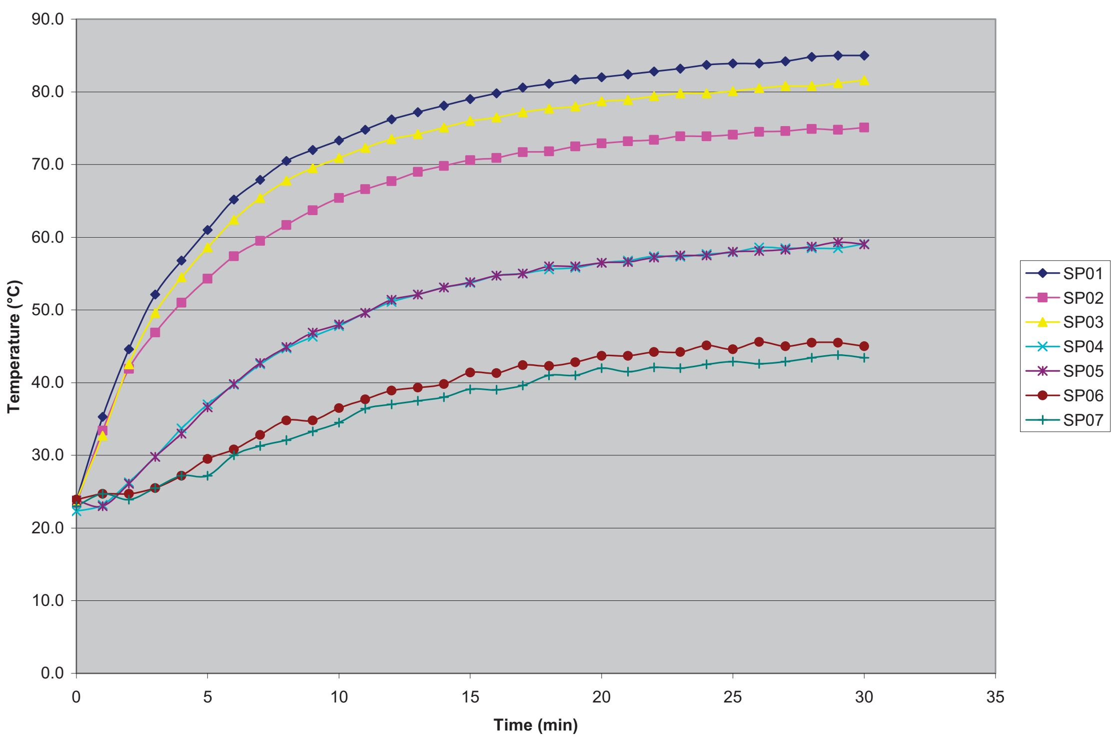

Figure 10. Temperature Profile ST-10 Construction (with CCL)

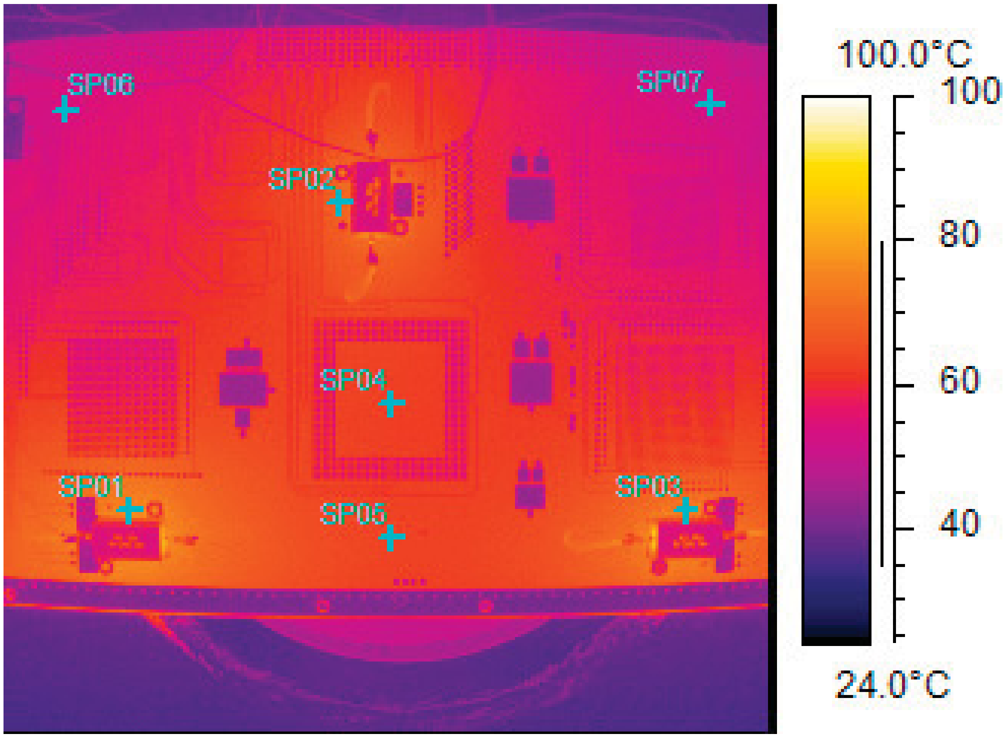

Figure 11. Infrared Image of Thermal Heat Distribution for ST-325 Construction (with CCL)

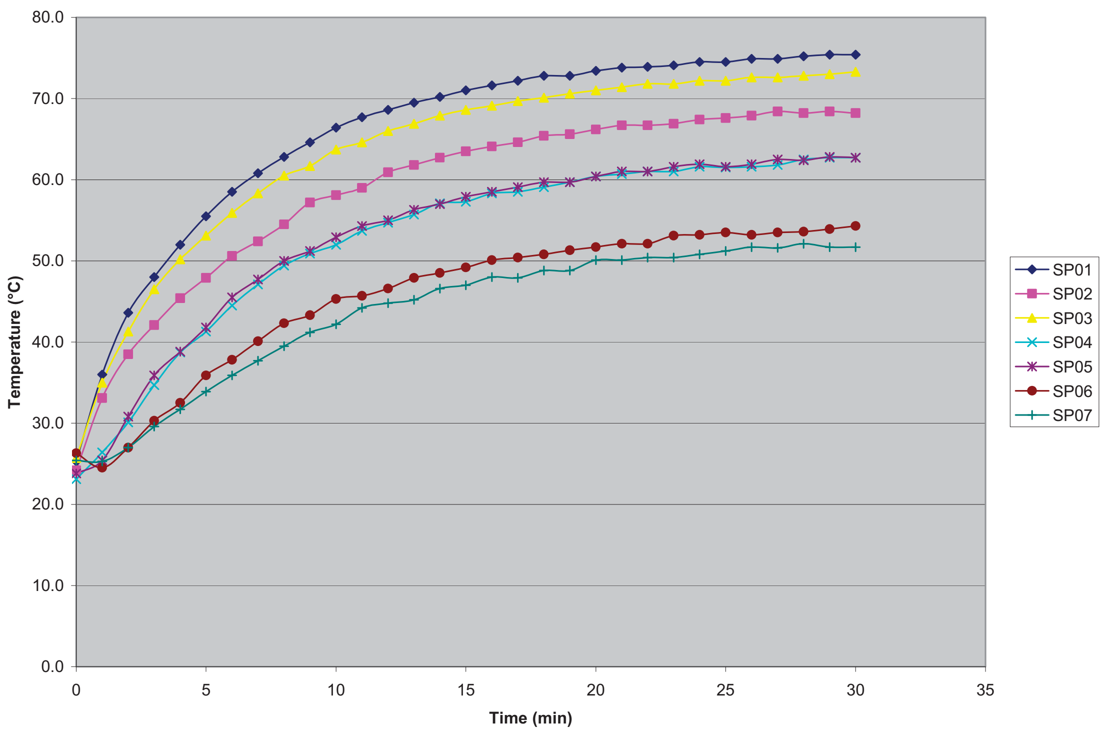

Figure 12. Temperature Profile ST-325 Construction (with CCL)

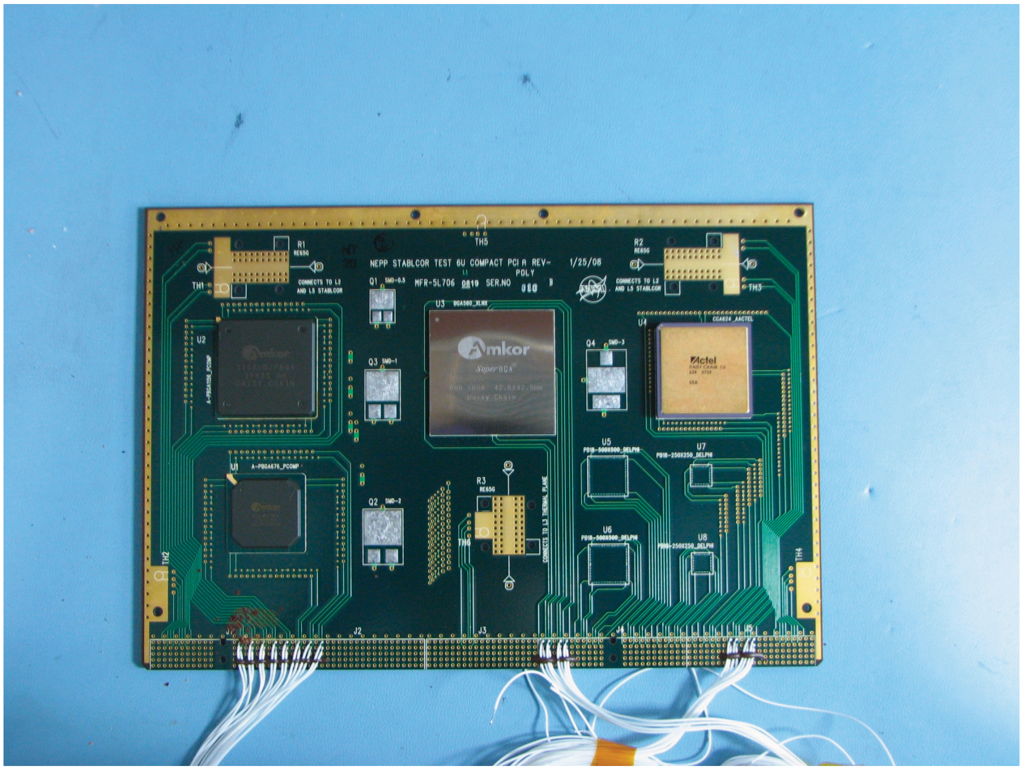

Figure 13. Printed Circuit Board with ST-10 CCL and BGA CGA Devices

4. Column Grid Array and Ball Grid Array Interconnection Reliability Testing

There were two different types of boards used for CGA and BGA interconnection reliability testing. There was one board used as a control sample with polyimide construction only and no CCL. Its cross-section was identical to the construction depicted in Figure 2. There were five boards tested with polyimide and CCL construction. The Stablcor CCL material was ST-10; the cross-section is depicted in Figure 3. All boards contained three BGAs and one CGA. The BGAs were in locations U1, U2 and U3. The single CGA was located at U4; see Figure 1 for reference. All of the BGA and CGA devices were constructed with internal metallic traces that form a continuous daisy chained electrical circuit when placed on the printed circuit boards. The BGA located at U1 was a plastic component with 676 balls. The BGA located at U2 was a plastic component with 1156 balls. The BGA located at U3 was a ceramic component with 560 balls. The CGA located at U4 was a ceramic component with 624 columns and is representative of what would be used for space flight hardware.

The six printed circuit boards were thermal cycled from -55°C to 125°C. The ramp rate was 3°C per minute and the dwell time at minimum and maximum temperature was 20 minutes. Each component was divided into four different circuits. Each circuit was measured with an ohm meter after every 75 cycles at room temperature. The average resistance for a closed circuit prior to thermal cycling was 1.2 ohms. The plan called for removing a circuit board from the chamber after a single failure, regardless of where it occurred.

5. Conclusions and Summary

5.1. Heat Transfer Testing

The temperature profiles generated during testing indicated excellent thermal transfer results for the board incorporating CCL ST-325. The printed circuit board type utilizing CCL construction with material ST-325 exhibited improved heat transfer over the printed circuit board type without CCL construction and the printed circuit board with ST-10 construction. The ST-325 construction provided a more efficient heat path through the board as indicated by lower temperatures at the resistor heat source (locations SP01, SP02 and SP03) and higher temperatures further away from the heat-generating resistors at locations SP04, SP05, SP06 and SP07. This can be seen when comparing Figure 11 to Figure 7. Figure 11 shows more "orange" area over the entire board with very little "white" area (hot), indicating effective heat spreading. Figure 7 shows more "white" area at the resistor heat source and less "orange" area. The ST-325 construction provided a significant reduction at the heat source "hot spot" at locations SP01, SP02 and SP03 of 9.1ºC, 8.4ºC and 8.6ºC, respectively. Refer to Figures 11 and 12 and compare them to Figures 7 and 8, which show the board constructed with polyimide (no CCL).

The temperature profiles generated during testing of the boards with ST-10 CCL did not exhibit an improved heat transfer over the printed circuit board without CCL. The heat transfer through the printed circuit board fabricated with ST-10 was almost identical to the heat transfer through the printed circuit board without CCL. This is evident by comparing the infrared images in Figures 7 and 9 as well as the temperature profile in Figures 8 and 10. The profiles and thermal images are almost equal. The ST-10 fabricated board should have exceeded the heat spreading performance of the board fabricated without any CCL. This part of the experiment was compromised by the attempt to design a test vehicle for use in multiple experiments. Due to a copper layer removed from the top and bottom portion of the cross-sectional stack-up, the ST-10 test vehicle had reduced thermal properties. The intent was to optimize the design, so it could also be used for the solder interconnection reliability test. The copper was removed for a more desirable thermal coefficient of expansion property to help reduce solder joint stresses. There are plans to rebuild the ST-10 test board to address this anomaly and rerun this portion of the experiment.

5.2. Interconnection Reliability Testing

It is recognized by the author that the sample size for this experiment was small and composed of a single control sample with no CCL and five samples with ST-10 CCL. Solder interconnection failures were expected once the number of thermal cycles exceeded 1000–1100 cycles, based on previous experiments internally and industry published data. The first two open circuits or failures occurred after 1230 thermal cycles on component U3, which is a large BGA device on printed circuit boards constructed with CCL. The next two failures occurred at 1350 cycles on component U3 on printed circuit boards constructed with CCL. The next failure occurred at 1494 cycles also on component U3 on the last printed circuit board constructed with CCL. The control sample printed circuit board constructed without CCL reached 1704 cycles without an open circuit or failure. The intent in the cross-section design of the printed circuit boards constructed with ST-10 CCL was to locate the CCL near the board surface to optimize the expansion of the board with the component and thus improve long-term thermal cycling reliability for soldered interconnections. It is evident in this small sample size test that printed circuit boards constructed with CCL did not improve the life of the soldered interconnections over the board that did not contain CCL.

6. Future Considerations

Printed circuit boards have been the mainstay of electronic packages and in use for decades. The design complexity of printed circuit boards has increased, and technology improvements in materials and processes have ensured that printed circuit boards will evolve and continue to be the substrate of choice in the foreseeable future. Incorporating CCLs in printed circuit board will provide properties that will expand the use of printed circuit boards for applications not previously envisioned. There are other factors to consider when utilizing CCLs within the circuit board lamination fabrication process. Those factors include solder joint reliability for long duration space missions exposed to extreme environments. The effects of radiation or the ability of structures of this type to shield against low levels of radiation still need to be determined. In addition, thermal issues associated with high density active electronic devices can require complicated and heavy mechanical features to facilitate heat transfer. This technology development was primarily focused on the performance of CCLs to improve heat transfer and improve solder interconnect reliability.

There is also considerable potential in leveraging this technology for super-computing space-borne applications where a system-in-a-chip or system-in-a-cube design requires advanced innovative solutions to manage heat.

Acknowledgements

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