A Structured Approach for Failure Analysis and Root Cause Determination for a Complex System Involving Printed Wiring Assemblies

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Abstract
Determining the root cause of a failure in a complex system is a demanding task that requires a structured and disciplined approach. From engaging the appropriate subject-matter experts, to verifying the failure in a particular subsystem, to determining the analytical techniques used, this process can be an overwhelming task. The objective of this paper is to describe the approaches and techniques used in a recent case history, and to provide a summary of methods engaged in analyzing the printed wiring assemblies (PWAs) that were involved in the failure.

One of the initial steps taken was to assemble a team of subject-matter experts (SMEs) from the various subsystems that comprise the complex system, prior to verifying the failure. During verification of the failure, it was critical that what caused the failure was not disturbed, otherwise critical information leading to the direct cause could be compromised. SME-developed tests were outlined and executed to perform the verification. Once the failure was verified, techniques such as fishbone diagrams were used for causal analysis. The use of root cause tools led the team from a systemic failure, down to a set of PWAs. Once the suspected root cause was determined to be within a particular PWA, a formidable list of analysis techniques were used to narrow down the precise cause. These included, but were not limited to: Bench-top electrical testing, visual examinations, real-time X-ray, Computed Tomography (CT) scans, Printed Circuit Board (PCB) cross-section analysis, scanning electronic microscope (SEM) evaluation, and data package pedigree review.

This paper provides a structured, methodical approach to failure analysis and root cause determination for a very complex system. It can be utilized as a guideline for other highly complex systems, or other systems where the cause is suspected to be within a PWA.

Introduction

The genesis of this paper resulted from a case history, discussed below, for an extremely complex and highly accurate electro-mechanical system (CS), consisting of approximately 20,000 individual piece parts. This CS is comprised of two subsystems for 1) measuring displacement and acceleration and 2) computing. The displacement and acceleration subassembly (DASA) consists of printed wiring assemblies (PWAs), sensors consisting of accelerometers and gyroscopes, resolvers, a stable platform, the associated cabling, bearings, connectors, etc. The computer subassembly (CSA), houses PWAs on a backplane.

The most basic function of this CS is that it provides vehicle position, velocity, and a measure of the vehicle attitude in inertial space, as well as providing steering commands for the vehicle. Depending upon the application for these type of systems, the complexity can vary widely. From CSs small enough to fit on oil and gas industry drill heads, to those in drones, commercial aircraft, satellites and missiles, the size, precision and accuracy for these systems and their functional attributes may vary widely.

The CS this paper applies to leans toward the higher-precision, multi-faceted category. Due to the highly intricate nature of the CS under discussion, the functional attributes are actually partitioned into major subsystems for design control purposes. As an example, the Velocity Subsystem (VSS) reports attributes that are provided by the accelerometers to algorithm routines for navigational purposes. The Attitude Measurement Subsystem (AMSS) provides angular displacement of a stable member, determined by gyroscopes, and uses this information for stabilization of that platform with reference to a gyroscope reference position. There are a number of other major subsystems that govern power, the input and output of data, communications and precision timing, electro-mechanical components and mission software. It is important to note that when anomalies occur in such a CS, comprising hardware and software from all the different subsystem's involved, the process for failure analysis and root cause determination can become somewhat complicated if appropriate procedures and guidelines are not followed.

The intent of this paper is to provide some guidelines to others who may also be working with similar systems, with some generic approaches and techniques that this investigation has found to be helpful particularly when the root cause is highly suspected to involve PWAs.

Process

When a CS failure occurs, the first step in initiating a failure analysis (FA) and root cause (RC) determination is data gathering. Identifying the facts, documenting them and holding a kick-off meeting are all key activities. These systems can fail in a factory environment, while undergoing characterization testing, or in the field. The information coming back to the team is often in different formats, and varies in available details. The more information that can be gathered, the stronger a position the team starts from.

The next key step is constructing a strong team of experts. Complex systems are often designed by smaller groups, who only work and understand their part of the larger project, and the interfaces to the larger system. Additionally, a system is not made up of just functions, but also parts, assemblies and materials. Selecting your key SMEs is critical. When looking at a CS failure, the typical team members required are in the following engineering disciplines: Systems, Electrical, Mechanical, Materials, Test, Software and Quality. Even if a CS looks to be a mechanical issue, no assumptions should be made, and all key team members should participate in the preliminary FA. Later in the process, the team can be reduced to a smaller set of SMEs, as work progresses.

A lead investigator is chosen to run the investigation, and it is their responsibility to coordinate the team, build a schedule and keep the team focused. There are a variety of techniques that can be used (Fishbone, 5-Whys, Fault Tree etc.) to support the brainstorming to find the root cause. In root cause analysis, not jumping to assumptions is important. The method chosen needs to be followed. Using a fishbone approach, the team starts to document the known defect and work out the factors that could contribute to the defect, starting with the general topics of Measurement, Material, Personnel, Environment, Methods and Machines. It helps to develop a hypothesis matrix for each factor within the fishbone. This hypothesis matrix includes a hypothesis as to why this factor is a contributor to the failure mode. Then, evidence is gathered to support the hypothesis as well as evidence that contradicts the hypothesis. A disposition is then made for that factor, based on evidence collected, as to whether that particular factor is an unlikely or possible contributor, or if more data is required to make an informed decision.

During the generation of the root cause analysis, it is the lead's responsibility to pull in additional team members to help brainstorm specific causal factors, as well as to manage the team in their actions to exonerate causes. It is often easy to go with one's gut feeling, but when working on a true root cause, the team needs to provide evidence to rule out a cause. It is at this stage that the investigation can be wrapped up quickly, or start to drag out with multiple experiments. The lead investigator is required to keep the team focused and disciplined, and prevent the other investigators from getting off track.

Depending on the CS failure type, there may be physical evidence that should not be disturbed. Methodical actions need to be worked through to support the testing needed to exonerate causes and bring the team to the probable causes. Complex systems that have failed cannot always be powered back up for verification of the failure. As failures and assemblies cannot always be re-created once pulled apart, documentation of the teardown, testing and inspections is critical. Non-destructive analyses, such as real time X-ray, can be very useful in verification before destructive methods are used. For electrical testing, factory tests on approved acceptance test equipment are great for validating build requirements, but when looking for the failure mechanism, test benches allow for a more detailed check-out of components and circuits.

Destructive physical analysis (DPA) is often a required step once all other options have been exhausted. Use of photographic methods allows for documenting evidence found throughout the process. Optical microscopes can be fitted with cameras to capture images, and visual images can be captured by SEMs as well. Just because an image is captured, it does not mean the team should immediately move to the next location. The SMEs of the FA should always review the images captured, and agree to move to the next point of investigation to ensure that all data has been looked at, captured and reviewed, before it is lost in the next FA step.

The best scenario is that a team is able to determine probable root cause from the evidence discovered through analysis, but this is not always the case. Working through the process, the team needs to build a case around the failure hypothesis with the pieces of evidence they can re-create. Program history is a useful key in building this case. Failures can be single events, but should be reviewed for patterns and larger issues in the design or manufacturing environment. The team is responsible for providing a final recommendation to the Failure Review Board (FRB) on the failure and the scope of the findings as they relate to other CSs and production.

When there is a CS failure in the field, it is an easy decision for the Internal Review Board (IRB) or the FRB to kick off a team to perform failure analysis, root cause and corrective action, but not all failures in a production facility identify themselves as candidates for investigation. At an appropriate time, the FA is handed off to the FRB which typically has many more tools at their disposal for analysis. Links between the factories, the field and the IRB/FRB need to be made. The IRB/FRB needs to review all decisions made at the field or factory levels, take responsibility to look for patterns, and determine what issues require escalation.

The IRB/FRB needs to be sure to balance the needs of the production lines to allow for some in process failures, while not letting systematic issues out of the factories and into the field. The following flow chart, Figure 1, is the recommended outline for the process documented above:

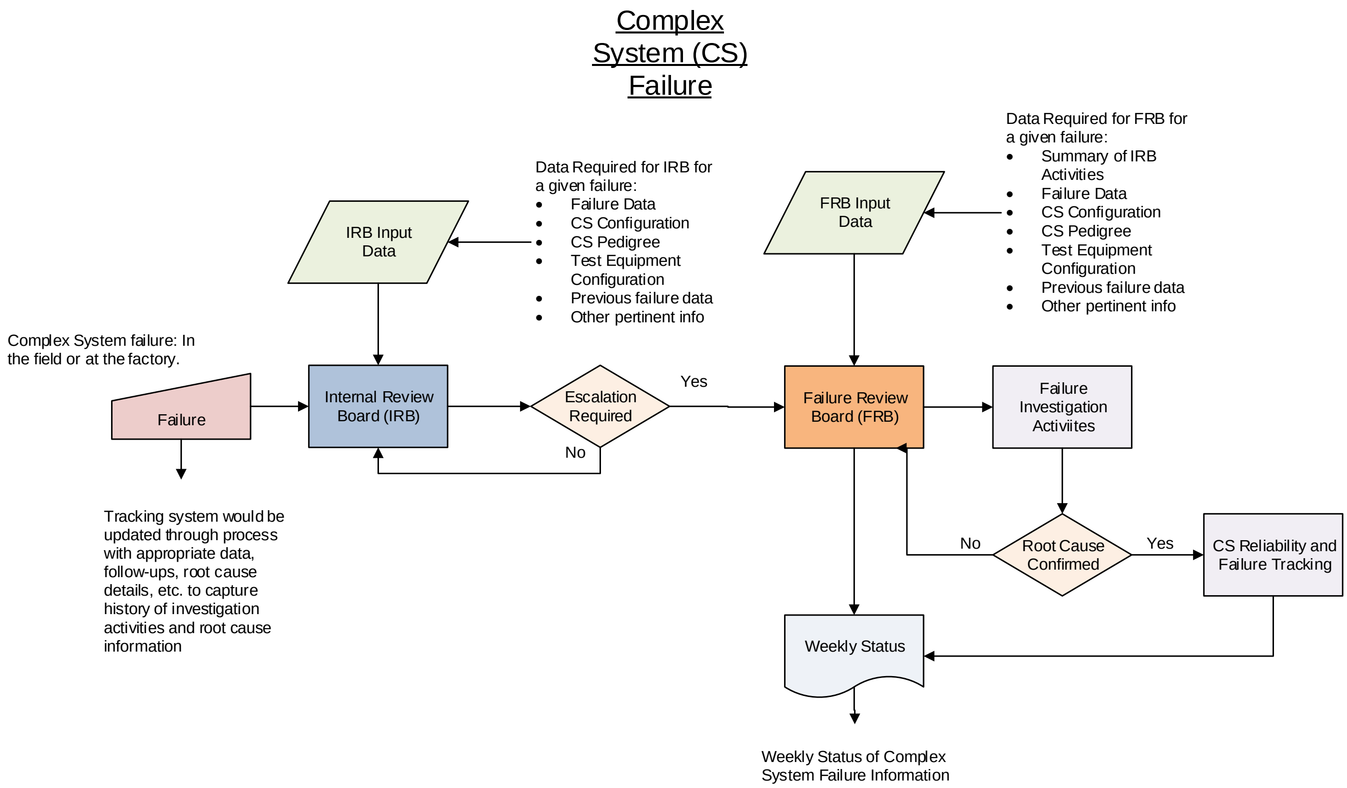

Figure 1 - Complex System (CS) Failure Flow

Failure Case history
At a location in the field, a test failure occurred with a CS. Relevant information was collected pertaining to the test station on which it was being tested, including the test station's software version. The test equipment used was then hooked up to an interface tester, to determine the status of the test station upon which the CS was tested. The test station ran nominally. Data dumps from the test failure were collected and sent to the design activity for analysis.

An initial meeting was held to assign relevant action items to the appropriate subsystem SME's, as part of the Internal Review Board (IRB) review process. A triage of all data was conducted to try to narrow down whether the issue was with the DASA or CSA. Within a week, the field site was directed to test the DASA separately from the CSA, using a known-working CSA. This was the first step in attempting to contain the issue to either major subassembly. Isolation and continuity checks were completed on the DASA prior to testing. The results of these were normal. The field site test results on the DASA confirmed that it was working nominally. Similarly, the CSA was tested with a known-working engineering development DASA, and once power was applied, a watchdog alarm was indicated and power was immediately removed. Additional testing, including verifying calibration parameters, was done with the DASA and these all passed. Approximately a month after the initial anomaly occurred, the CSA was shipped back to the assembly factory for further investigations.

Once at the factory, continuing IRBs were held to trouble shoot the CSA. Prior to removing the PWAs, a continuity and resistance test was performed. The results from these tests were compared to the same tests performed 6 months prior, and they compared favorably. A number of PWA's were removed from the assembly and re-tested; this was done on the test station previously used for final acceptance testing of the same PWAs prior to going into the CSA. All mating connectors were visually inspected. Also, critical wiring harnesses were removed and tested on an automated isolation and resistance test station used just for this purpose.

All PWAs tested on the PWA acceptance tester were exonerated. These included subsystem specific PWAs, processor PWAs, as well as memory-specific PWAs. All PWAs were removed from the CSA backplane, and the backplane was completely visually inspected. The bottom cover of the CSA was also disassembled, so that both sides of the backplane could be inspected. There were two PWAs that had visual defects noted, and therefore were not retested. The first PWA, identified here as PWA1, had a component CR500, Figure 2, that had a brown appearance on the part and a solder glob, Figure 3, on the external side of the component. The second PWA, identified here as PWA2, had a severely burned area near reference designator R517, Figure 4. On the backside of the PWA, opposite to the burned mark, there was evidence of discoloration near reference designator C22, Figure 5. Approximately three months after the test failure, the entire CSA, with all PWAs, was returned to the design activity for further analysis.

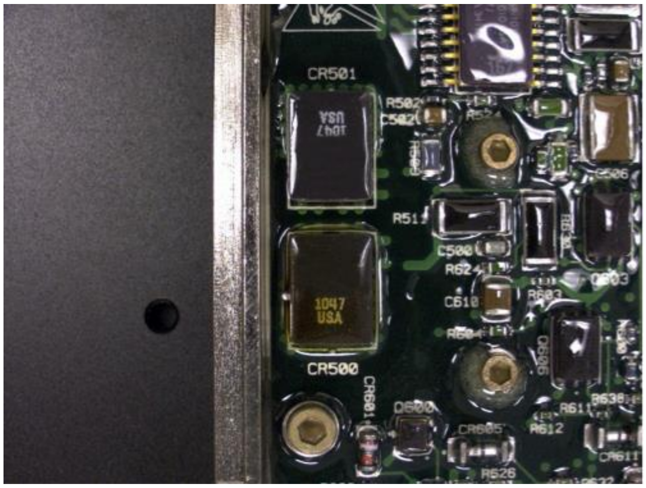

Figure 2 - PWA1 Discolored CR500

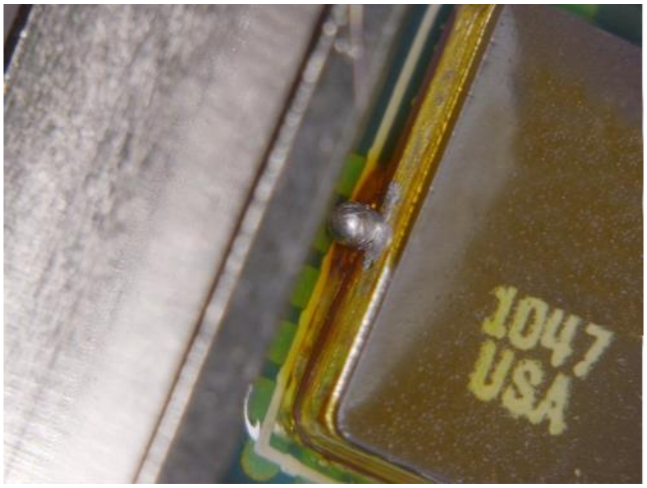

Figure 3 - PWA1 Solder Blob on Edge of Component CR500

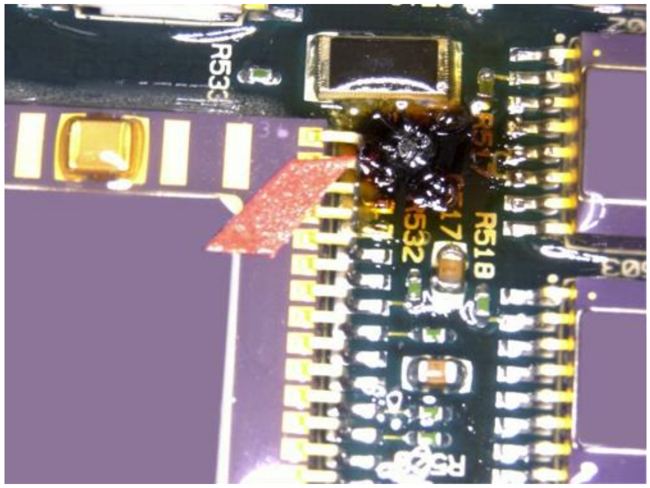

Figure 4 – PWA2 Burn Mark near R517

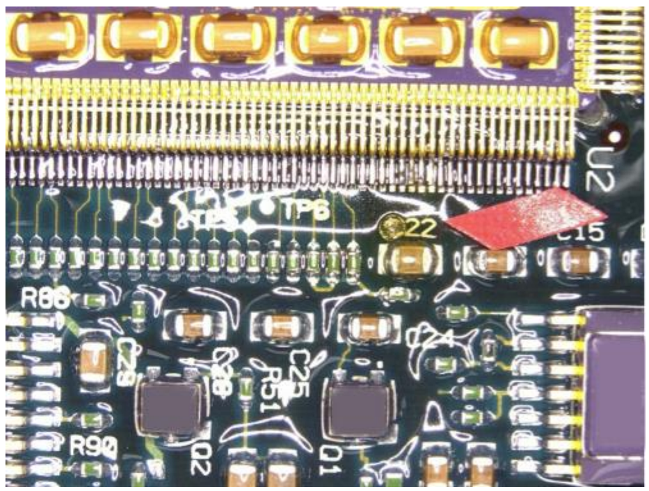

Figure 5 - PWA2 Opposite side of PWA Burn Mark C22

The initial investigation that occurred at the factory, guided by the IRB on a frequent basis (several times a week), attempted to narrow down the cause of the anomaly during field test to a specific PWA(s) within the CSA. Without presupposing what the true root cause of the failure was, once at the design activity, the failure investigation was escalated to the Failure Review Board (FRB), and they led the investigation from this point on. Initially, an independent visual inspection was performed on all the PWAs within the CSA. The independent inspection confirmed what the factory had found, and based on these results the focus of the investigation centered on these two PWAs: PWA1 and PWA2.

Some preliminary work was performed, such as reviewing the defects on the two PWAs, relative to the circuitry within the PCBs. Much focus was placed upon the PWA2 burned area and the buried vias in the vicinity. Both PWAs also had real-time X-rays taken. A solder ball was noticed under the CR500 Schottky diode component on PWA1, and the solder blob on the side of the component was evident as well, Figure 6. Isolation tests between all power outputs and grounds were conducted on PWA1. All measurements were nominal, except results confirmed a short on the diode CR500. Isolation tests between all power outputs and grounds were also conducted on PWA2. This confirmed a short (0.8 ohms) between a 3.3V power plane and ground. The path that was checked is typically 5K-6K ohms. Other measurements were nominal. The short certainly warranted further attention. This ended up being the focus of the failure investigation. It was believed that the solder ball under CR500 was a result of overheating the component. The overheating of CR500 was later to be determined to be a result of the short on PWA1.

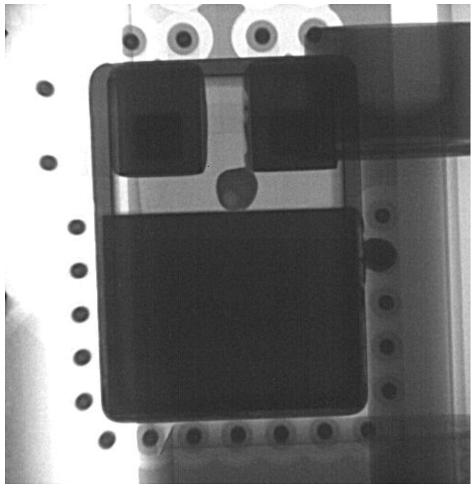

Figure 6 - PWA1 CR500 Real Time X-ray

Since the focus of this investigation now centered on the PWA2 and its corresponding short, the failure analysis team created a fishbone diagram (a.k.a. Ishikawa diagram). This diagram provides a systematic way of categorizing the potential causes of a problem in an attempt to narrow down the root cause. The fishbone diagram that the team of experts created did not rule out the other PWAs, but certainly focused on the two PWAs mentioned above, and it centered the investigation on the short found in PWA2. An early version of the diagram used is below in Figure 7.

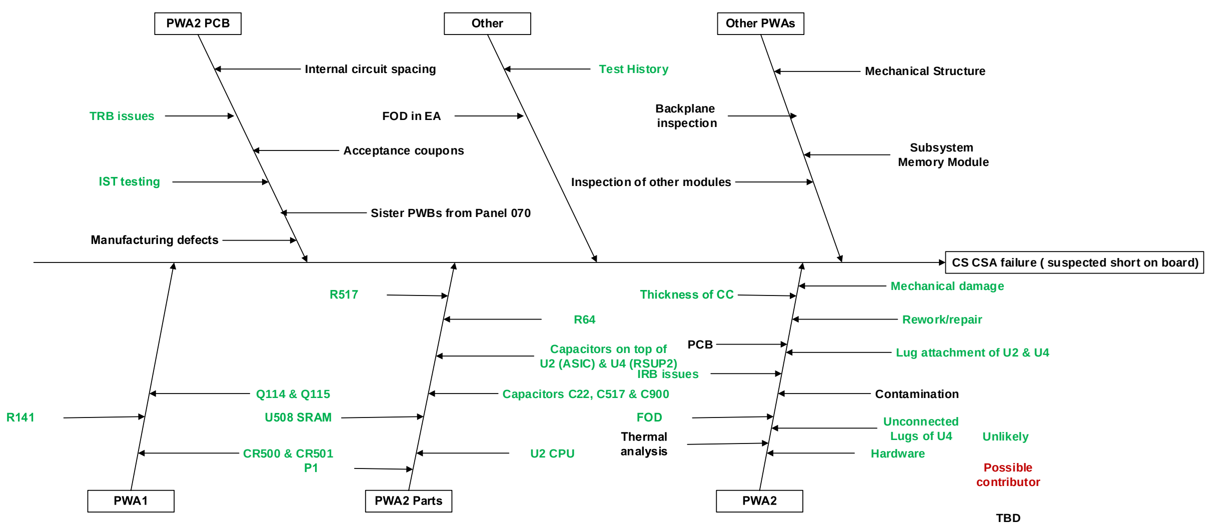

Figure 7 - Fishbone Diagram for Computing Subassembly (CSA) Failure

Each branch of the fishbone was then methodically reviewed, and numerous potential causes were eliminated. These three main branches on the fishbone (Other, Other PWAs and PWA2) were essentially eliminated as possible contributors. This was accomplished after thorough investigation of any and all data available from a pedigree review of all components (parts and PCBs) going into the assemblies. This included a review of waivers or deviations that may have been approved previously, and an assessment of their impact (if any) on the failure. It also included a review of acceptance test data and factory build information of each of the PWAs, to look for any off-nominal conditions.

For PWA1, some further attention was paid to the CR500 (and its sister diode CR501). The team reviewed the system schematics and interconnect drawings, as well as the critical design review (CDR) presentations for PWA1, with an emphasis on the detailed thermal analysis. The review indicated that the CR500 is the PWA1's hottest part, and as a result of this, additional vias were added to the PCB to aid in heat dissipation. It was noted that the possibility of a thermal runaway on two diodes in parallel (CR500 and CR501) was examined at CDR, but it was not included within the CDR materials.

Therefore, an updated analysis was conducted to reflect a thermal environment where one diode carries all the input power. This analysis indicated an acceptable temperature variation.

A SEM, using Energy Dispersive X-ray Spectroscopy (EDS), analyzed the solder ball on the side of the component CR500. It was determined to be tin/lead solder, similar in composition to the solder used to assemble the PWA. This confirmed that the gold/tin braze, used to assemble the component CR500, did not reflow. The initial eutectic temperature of the Gold/Tin braze material is approximately 280C. However, both the lid and package are gold–plated, so that increases the melting temperature somewhat. The next step was to send the component to an independent failure analysis laboratory[1]. There, SEM imaging, as well as CT X-ray techniques, were used. The CR500 Dual Schottky diode, when electrically tested, exhibited a short circuit. It was found to have one diode catastrophically damaged, likely from an electrical overstress event (EOS).

For PWA2, much greater attention was placed on its analysis. The PCB manufacturing lot that the board in question came from was closely scrutinized. The lot involved 8 manufacturing panels, date code 1151, 3 up on a panel. The PCB is a 16-layer polyimide board, with plated through hole (PTH) vias (1066 µm), microvias (152 µm) and buried vias (381 µm). Conductive via fill material fills the buried vias. The SN's of the panels ranged from 064 to 071, inclusive. PWA2 came from panel SN 070. Acceptance of panels is based upon: Conformance coupons, of each via type from diagonal corners of the panel, one set in X and the other set in Y directions. Two IST coupons were tested per panel for microvias and 2 coupons were tested per lot for PTH and buried vias.

After particular components were cleared from being a cause, the PWA2 was CT scanned. The information provided by the CT X-ray was extremely beneficial in defining a plan for micro-sectioning the PWA2. The scan clearly showed a separation of vias, as well as delamination of layers, Figure 8. A number of other activities centered around evaluating the PWA2 and its PCB. A thermal simulation of the PWA2 was performed, with the goal of duplicating the thermal damage of the PCB due to a suspected short between the 3V plane and ground. The simulated temperature levels were found to correlate with the observed thermal damage on the PCB. The simulated temperature levels were consistent with the solder re-flow patterns observed by visual inspection on the outer layers of the PCB. Also, the thermal transient simulations actually reached expected temperatures in a period consistent with test data fault code timing diagrams obtained from the field failure. Another path of inquiry led us to a visit with the PCB manufacturer. A thorough review of all documentation associated with the 8-panel lot was conducted from looking at material certificates, floor travelers log books and anything remotely associated with this lot of panels. Nothing unusual was found during this exhaustive review at the supplier. Another process initiated during this microsection evaluation was that an assembled PWA (from the same panel 070 as our failure) was placed on long-term bench testing, for monitoring purposes. The team also resolved that the EOS condition on the CR500 on PWA1 was determined to have been caused by the short between the 3.3V plane and ground from PWA2.

An extensive microsectioning plan was developed for the PWA2. This plan utilized information from the CT scan, in order to determine as much information from the failure site prior to actually cross-sectioning it. The plan that was developed evaluated microsection coupons from the PWA2 itself (1 for the failure site and 2 for control purposes), as well as independently evaluating the acceptance coupons from this panel (070, as well as all the other panels within this lot). The same amount of material (about 0.08 µm) was removed at each polishing step prior to examining it under a microscope. This was limited, so that we would not overshoot critical sites. About 12 vias were examined in all, including the actual failure site. In total, almost 13 mm of the failure site coupon was removed during the microsection process. Resistance measurements were taken throughout the process, to monitor whether the short still existed on the mount or not. The short 'went away' as the coupon was polished through the actual failure site via. The delamination voids were vacuum-filled with epoxy, so that continued polishing would not cause major disruption to the mount. PCB lots made at the supplier from a period of time prior to, and after, the DC 1151 were also reviewed. This review concentrated on reviewing the conformance coupons to determine if we could see any trends, and to exonerate other PWAs that could potentially be affected by results found in the 070 panel.

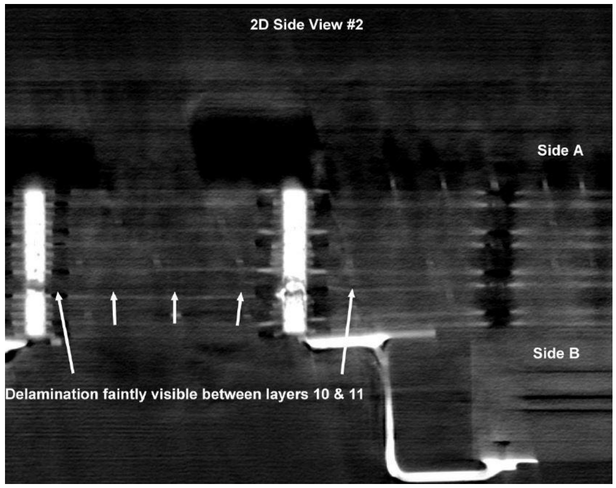

Figure 8 - PWA2 CT Scan

Failure Analysis Root Cause

Failure mechanism of the PWA2 has been determined to be a defect in the PCB. This conclusion is based on a number of investigation steps, including the sectioning of the three microsection coupons removed from the failed PWA2, and the findings discovered during the re-inspection of the panel 070 conformance coupons as well as the other panel conformance coupons within the same date code. As a result of the failure analysis, evidence led the team to the conclusion that the mechanism causing the failure of the CS within the CSA is a foreign inclusion, which acted as a catalyst in propagating a crack, thereby providing a pathway for copper plating and plating residue to travel up the crack. This condition reduced the design clearance distance between a buried via (which is signal GND) and layer 11 plane (which is a 3.3V plane). This reduced distance had been breached by a conductive filament growth facilitated by plating residues over time.

Once the short was established, the heat generated by the short caused burning and melting of the dielectric material, creating carbonization (electrically conductive), which further propagated the short. The electrical short measured in the failure site coupon mount was the result of the carbonized material in the PCB.

The justification for the failure mechanism was based upon a number of observations. Foreign inclusions exceeding the acceptable length in IPC 4101 were found in both the conformance coupons of panel 070 (the manufacturing panel that the failed PWB came from) and the three coupons removed from the failed PWA2. When other conformance coupons from this date code were reviewed, there were some foreign materials (possibly the result of Automated Optical Inspection AOI rework) found through dark field and SEM analysis. Figure 9, below, shows the locations where the three sections were taken. Figure 10 indicates resin-like inclusions found in one of the conformance coupons from panel 070. The right photograph is bright field, and the inclusion was found to be resin-like material. It is important to note that it was just slightly noticeable using standard light field illumination, but when dark field was used (which is not a current requirement), the defect could be seen more clearly in the left photograph. After some grinding and polishing, that inclusion was determined to be copper. IPC 4101 does not allow any encapsulated metallic particles of any size, whether in a core or prepregnated material. Figure 11 is another example of a nonconforming inclusion, found in one of the two control coupons from PWA2. This was also determined to be a resin-rich, crack-like inclusion.

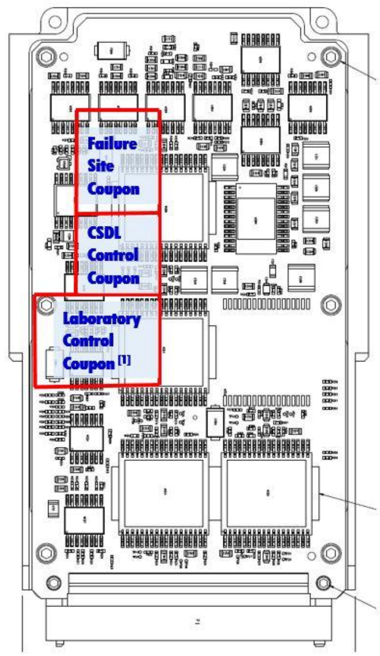

Figure 9 - Module Section locations (red lines indicate sectioning cut planes)

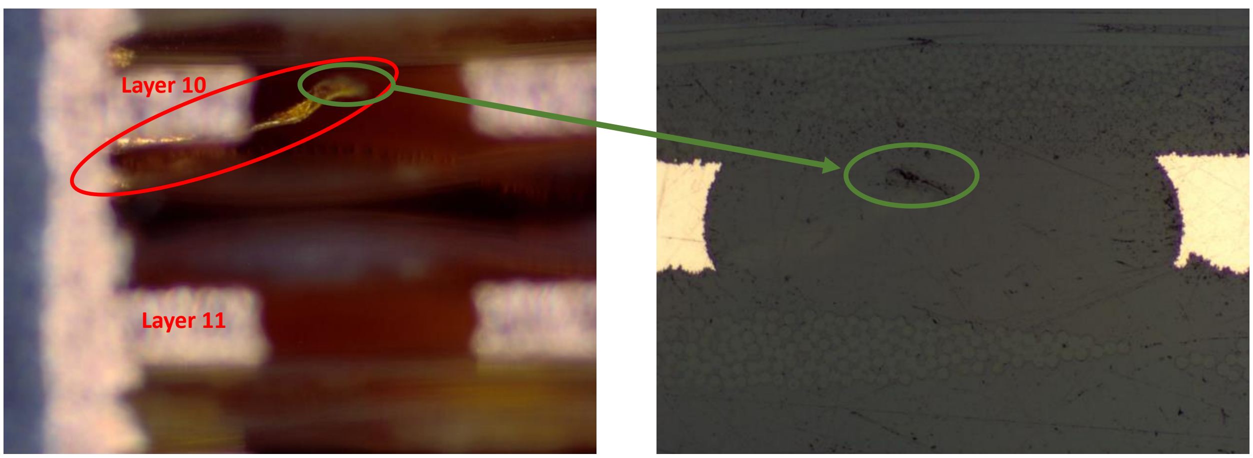

Figure 10 – Panel 070 Acceptance Coupon (Dark Field on left, Bright Field on Right)

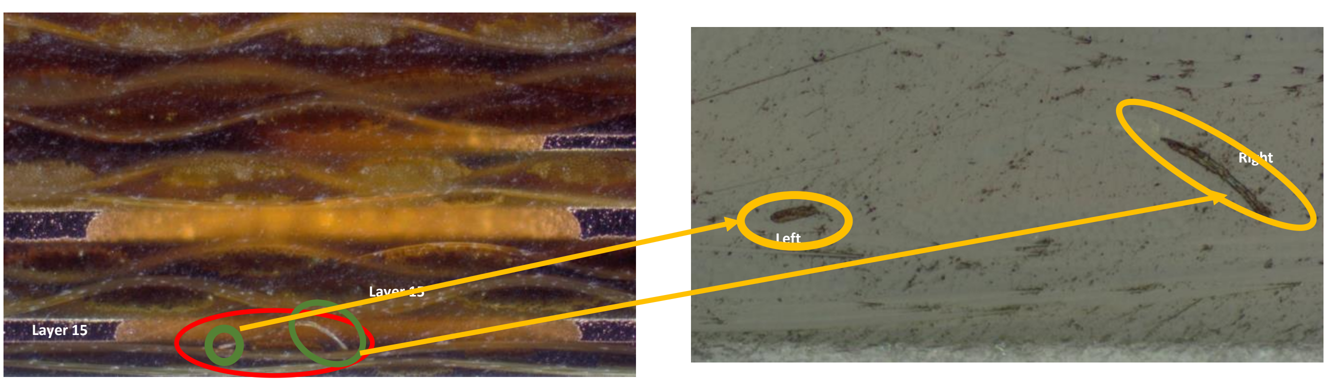

Figure 11 – Laboratory Control Mount [1] (Dark Field on left, Bright Field on Right)

Sectioning of the failure site coupon revealed copper within the fiber bundles, along with chlorine and believed to be a result of copper-plating residues.

Figure **12** is a dark field illumination picture of fiber bundles with the copper plating residues. Use of SEM and EDS, Figure 13 and Figure 14, shows the presence of copper, chlorine and sulfur in the glass bundles. The only mechanism that accounts for the presence of all three is a defect in the resin (inclusion with crack) that allows for the wicking of the plating solution for a plated via. The presence of moisture was also discovered within some of inclusions with cracks during this evaluation.

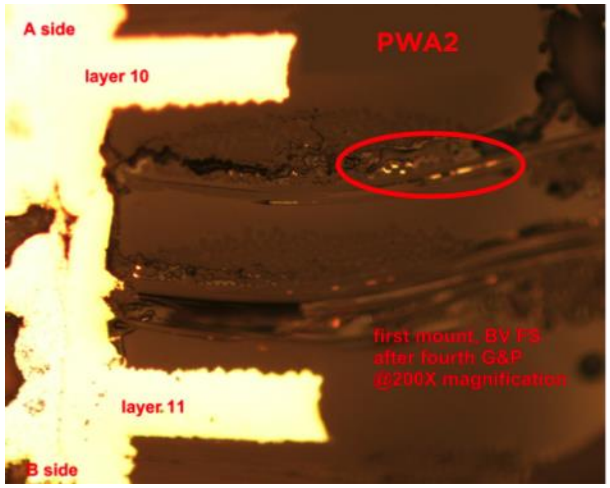

Figure 12 - Failure Site Coupon Mount (Dark Field)

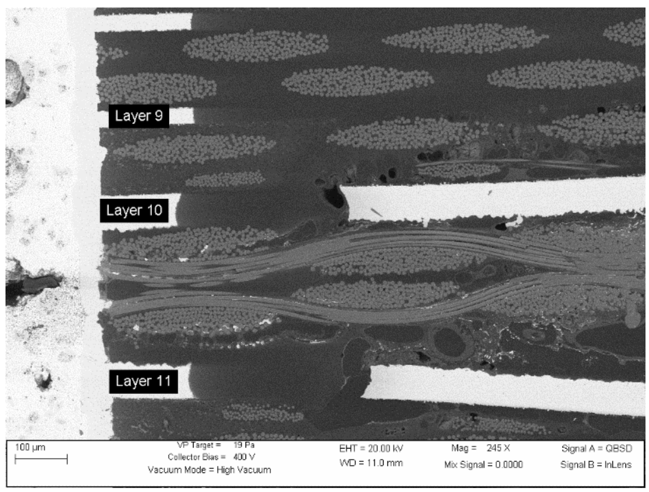

Figure 13 - Failure Site Coupon Mount (SEM view)

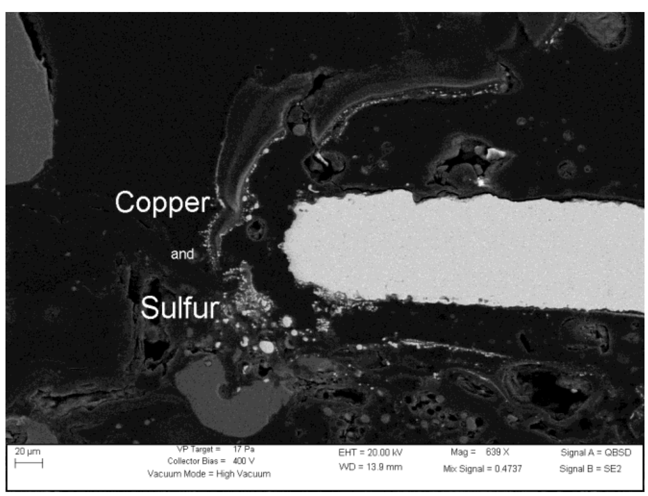

Figure 14 - Failure Site Coupon Mount (close up SEM View)

The sectioning of the failure site mount provided evidence that the epicenter of the failure is the buried via (signal: GND), under an unused pin 36 of U508, Figure 15. This buried via is the only one with melted copper and melted conductive via fill material. Layer 11 plane (signal: 3.3V) shows melted copper at the right edges of the via around the clearance area, around this buried via. The other vias examined in the mount, Figure 16, show cracks, separations and gaps but provided no evidence of melted materials.

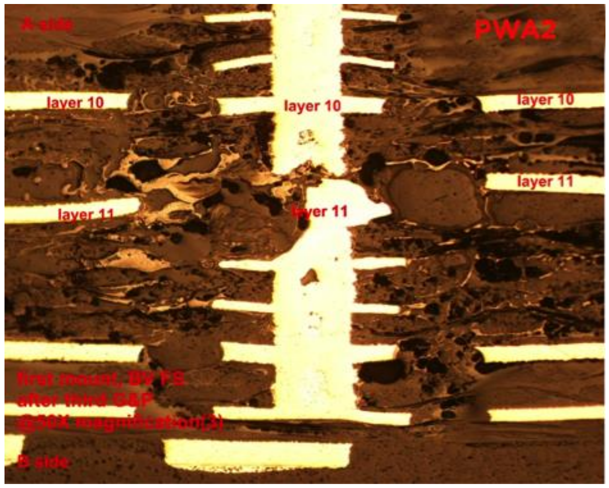

Figure 15 - Failure Site Buried Via (showing melting, Dark Field)

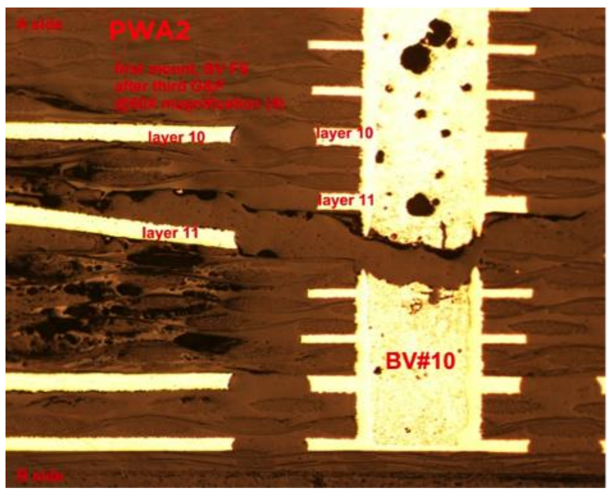

Figure 16 - Other Buried Via (only show separation, Dark Field)

The filament that breached the reduced clearance between the ground buried via and the power plane is CAF (Conductive Anodic Filament) facilitated by plating residue. Conductive Anodic Filament is an electrochemical process involving the transport of a metal through, or across, a nonmetallic medium under the influence of an applied electric field. A filament formed from the end of the foreign inclusion from the ground buried via to the power plane (P3.3V). This resulted from the combination of electrical bias (P3.3V and GND), plating residues, moisture (RH {relative humidity}) and time.

As mentioned above, the conformance coupons of date codes before and after DC1151 were inspected. A total of 8 other date codes were inspected, and while some inclusions were seen, nothing in the acceptance coupons would fail program requirements (including IPC 4101), or contained any other mechanisms (cracks or plating residue) found in the failed PWA2. All the conformance coupons were inspected from the other 7 panels within DC 1151. There were several panels that indicated inclusions exceeding requirements. All PWAs from these nonconforming panels were subsequently dispositioned appropriately.

Proposed Corrective Actions:
Several corrective actions have been developed as a result of the root cause investigation, and are still being evaluated for incorporation into program planning requirements. In summary, these include:

1. Add PWB inspection requirements of acceptance coupons to include dark field inspection
2. Require a minimum number of CS 'burn-in hours'. The sister PWA was on test with no issues for twice as long as the PWA2 was tested within the CS.

3. Recommend flowing down cleanliness requirements to PCB suppliers for the lamination booking. There was some FOD found during our investigation in coupons, and this would be an attempt to reduce that.
4. Change PCB material with multi-functional epoxy.
5. Add controls on supplier inner layer AOI rework.

Conclusions

The processes used in this case study followed a very deliberate sequence of events, in an attempt to narrow down the root cause of a failure in a very complex system. The flow in Figure 1 was followed as a structure to guide the program through the triage of data and events. Through a series of tests while the CS was still at the field location, an IRB was formed, and through their work, it was determined that the failure was within the CA. Subsequent to that, IRBs were held at the factory to further narrow down the failure to individual PWAs.

Once this was accomplished, the CSA and all its individual components were sent to the design activity and the matter was escalated to FRB standing. At this location, the design activity had many more tools at its disposal to investigate failures than were available at the factory. Through the use of the many analysis tools previously discussed, the FRB was able to determine the most probable cause of the CS failure and recommend corrective actions to prevent recurrence.

Acknowledgments

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References

[1] Crane Naval Surface Weapon Center, Crane, Indiana

A Structured Approach For Failure Analysis and Root Cause Determination for a Complex System Involving Printed Wiring Assemblies

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Introduction

- Genesis for this paper – Actual case history for a very complex electro-mechanical system (CS).
- This CS provides vehicle position, velocity, and a measure of the vehicles attitude in in inertial space, as well as providing steering commands.
- Higher precision, multifaceted, more complex than typical. Functional attributes are partitioned into major subsystems.
- Provide guidelines for very complex systems using some generic approaches and techniques, where the root cause is suspected to be with printed wiring assemblies (PWAs).

Process for Failure Analysis and Root Cause

- Initial steps include data gathering and not disturbing the setup.
- Form a strong team of subject matter experts (SMEs) with cross functional responsibilities. These initial activities usually involve an Internal Review Board (IRB).
  - Systems, electrical, mechanical, materials, test, software, quality, etc
  - Select a lead investigator for coordination, scheduling, assigning tasks
- Resist forming conclusions without substantive objective evidence

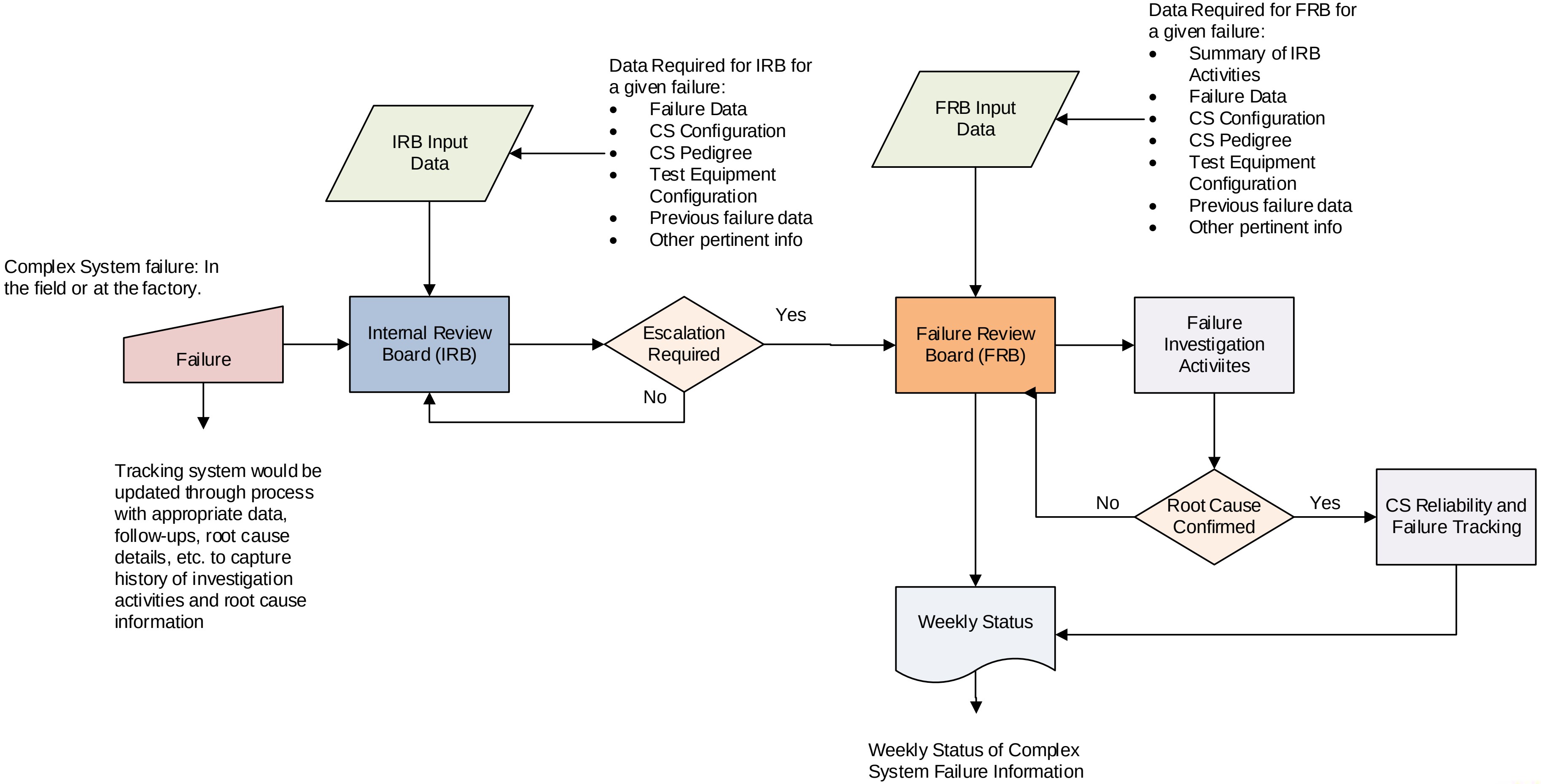
Process for Failure Analysis and Root Cause

- After initial investigations are concluded, activities often escalate to Failure Review Board (FRB) that has more responsibility than the IRB.
- Use well proven root cause techniques including fishbone (Ishikawa), 5 Whys, Fault Tree, etc.
- For fishbones, develop hypothesis matrices for possible factors. Include a hypothesis why each factor may be a contributor to the failure mode. Then evidence is collected for and against the hypothesis. The more compelling data then leads to a disposition for that factor as a cause (unlikely, possible, need more data)

Process for Failure Analysis and Root Cause

- Utilize non destructive and destructive techniques.
  - Visual, X-ray, electrical testing, Scanning Electron Microscopes (SEM), Computed Tomography (CT)scanning, Destructive Physical Analysis (DPA) and others
- Use of engineering models can help simulate physical actions to confirm or reject specific hypothesis.
- Bench tests simulating physical scenarios can also be used to confirm or reject hypothesis.
- The team is responsible for reviewing all applicable data.

Complex System (CS) Failure



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Failure Case History

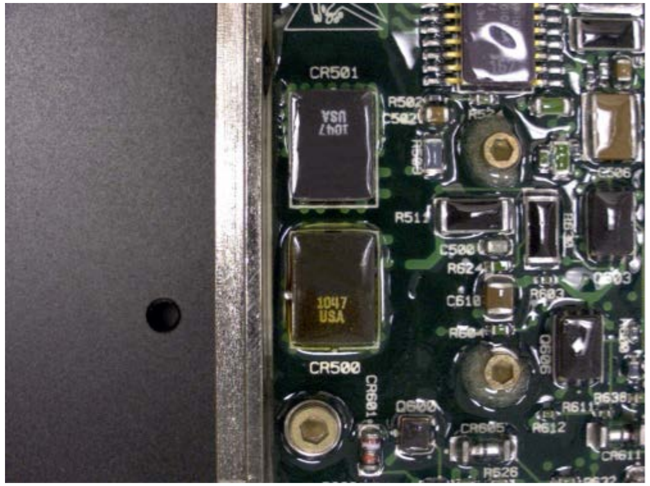
- A CS failed during testing in the field. Data collection, through IRB convened with SMEs from relevant subsystems.
- Troubleshooting was conducted to determine if test equipment was ok through the use of a simulator.
- Test data and timing diagrams were analyzed. Field testing was conducted to determine whether the Displacement and Acceleration Subassembly (DASA) or Computing Subassembly (CSA) were at fault.
- CSA was shipped back to the factory after a month of activity.

Failure Case History
Internal Review Board (IRB)

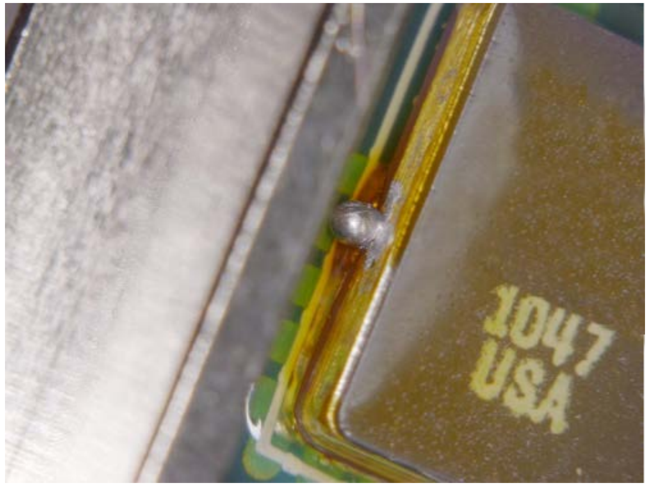
- IRBs continued at the factory. Very frequent. Each step in the process was deliberate and cautious.
  - Continuity and resistance, values compared to previous results
  - Visual inspection of all PWAs and backplane. Retesting of some PWAs on acceptance test equipment exonerated these.
  - Visual inspections of connectors and harnesses, continuity and isolation testing of harnesses
  - Two PWAs had visual defects and were not placed on the test station

Failure Case History

- PWA1: CR500, a dual Schottky diode had a brownish appearance, indicating over an overheated condition. A solderball was also seen attached to the package side.



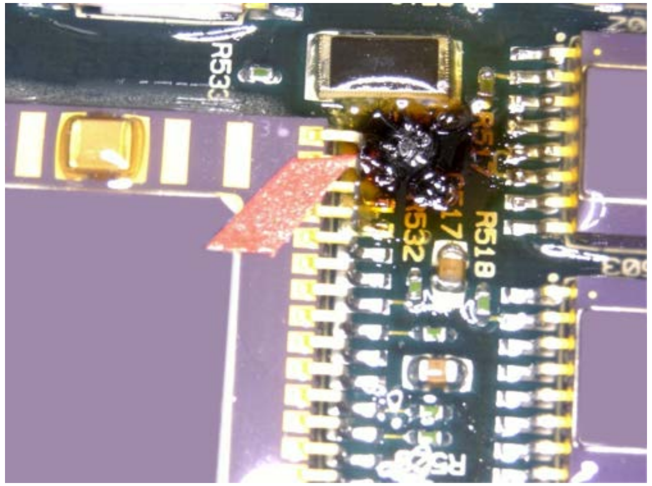
Overheated Component



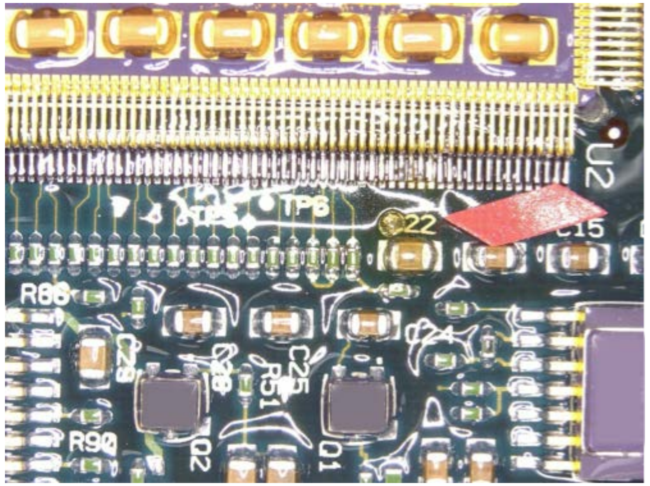
Solder Ball

Failure Case History

- PWA2: Top side had a severe burn mark near R517. Opposite side had discoloration near C22.



Burn mark near R517



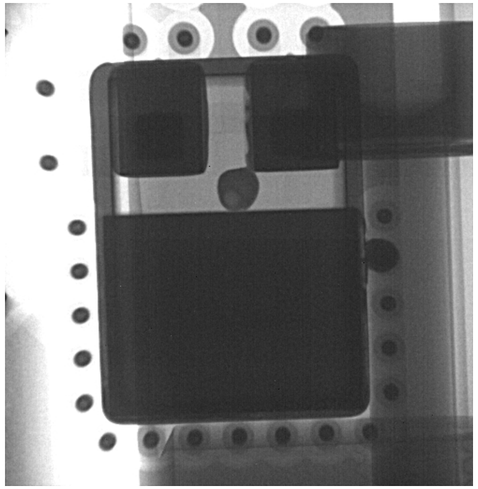
Discoloration opposite side C22

Failure Case History
Failure Review Board (FRB) Escalation

- The matter was escalated to the FRB at the design activity.
  - Design activity has more analysis tools at its disposal than the factory.
  - Preliminary activities included visual inspections and Real time X-ray for PWA1 and PWA2.
  - Isloation tests between power and ground were conducted for PWA1 and PWA2.
    - PWA1: Nominal except short detected on CR500
    - PWA2: Short detected (0.8 ohms), nominally 5-6K ohms between 3.3V power plane and ground plane.

Failure Case History

- The real time X-ray of PWA1 indicated a solderball underneath the component, likely causing the short.
- Did PWA1 cause the condition on PWA2 or vice versa?

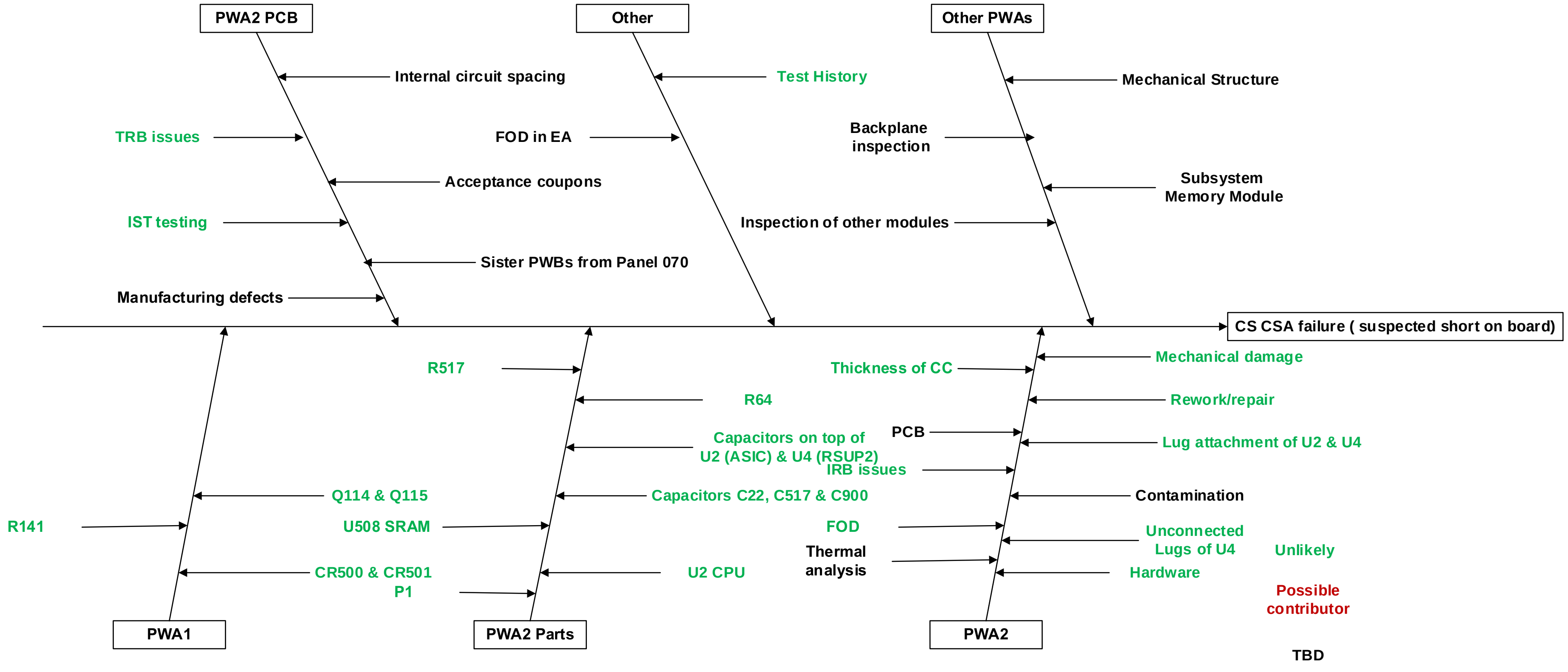


CR500 Real time X-ray

Failure Case History Fishbone Creation

- In order to address this question, and to get to the root cause, a fishbone diagram was developed.
  - It provides a systemic way of categorizing the potential causes of a problem in an attempt to narrow down the root cause.
  - The FRB did not presuppose what the cause was, considered all the PWAs but certainly concentrated on PWA1 and PWA2.

Failure Case History Fishbone Creation



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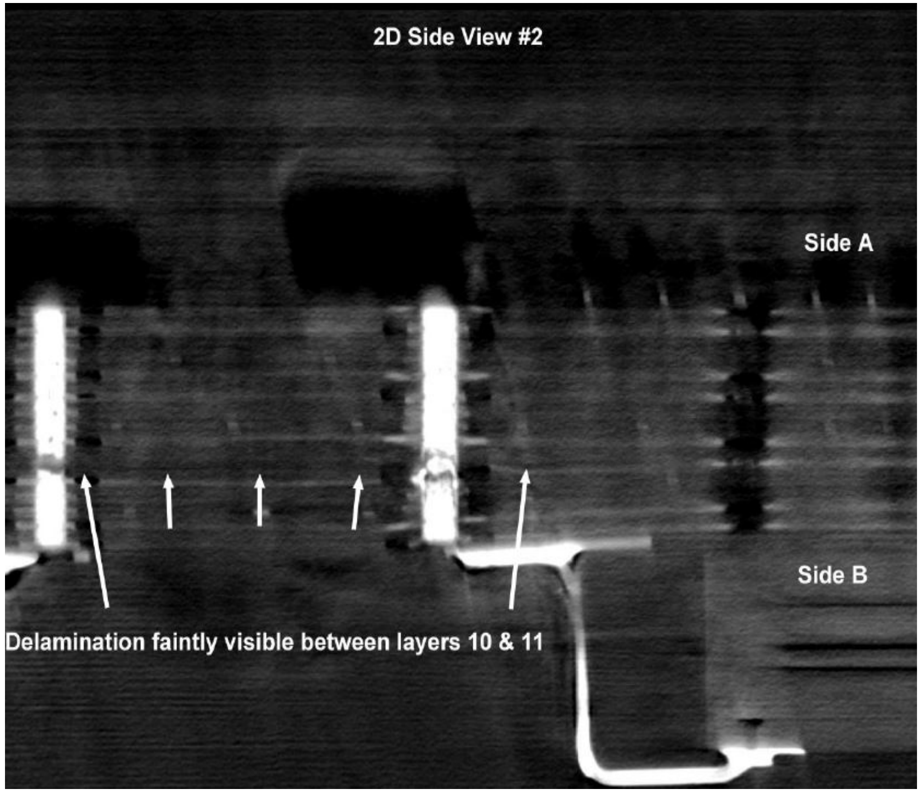
Failure Case History Fishbone

- Each branch was methodically reviewed and numerous potential causes were eliminated.
  - Other, Other PWAs and PWA2(fab issues) were eliminated
  - PWA1: CR500 and CR501
    - Reviewed system schematics, interconnect drawings, critical design review (CDR) presentations, thermal analysis.
    - Review confirmed that CR500 is the hottest part, added vias after CDCR. Thermal runaway condition reconfirmed. One diode can carry all the input power with acceptable temperature variation.
    - SEM using energy dispersive X-Ray spectroscopy (EDS) confirmed solder ball was same as reflow paste and did not come from package braze material.
    - Independent destructive physical analysis (DPA) of CR500, using SEM and CT scans determined that its failure was from electrical overstress (EOS)

Failure Case History Fishbone

- PWA2:
  - Suspect components were cleared leading to critical emphasis placed on the PCB
  - PCB: 16 layer, polyimide construction, PTH vias (1066 µm), microvias (152 µm) and buried vias (381 µm). Buried vias have conductive fill. 8 panels in the manufacturing lot. PCB in question from panel 070.
  - Pedigree review at the manufacturer was conducted. Nothing unusual was found.
  - Thermal simulation was conducted. Simulated temperature levels were consistent with the solder re-flow patterns seen on the PWA2. Simulated thermal excursions were consistent with test data fault code timing diagrams obtained from the field failure.
  - Performed CT scan. The scan clearly showed a separation of vias, as well as delamination of layers. The information provided by the CT scan was extremely beneficial in defining a plan for micro-sectioning the PWA2. The same amount of material (about 0.08 µm) was removed at each polishing step prior to examining it under a microscope.

PWA2 CT Scan



2D Side View #2
Side A
Side B
Delamination faintly visible between layers 10 & 11

Failure Analysis Root Cause

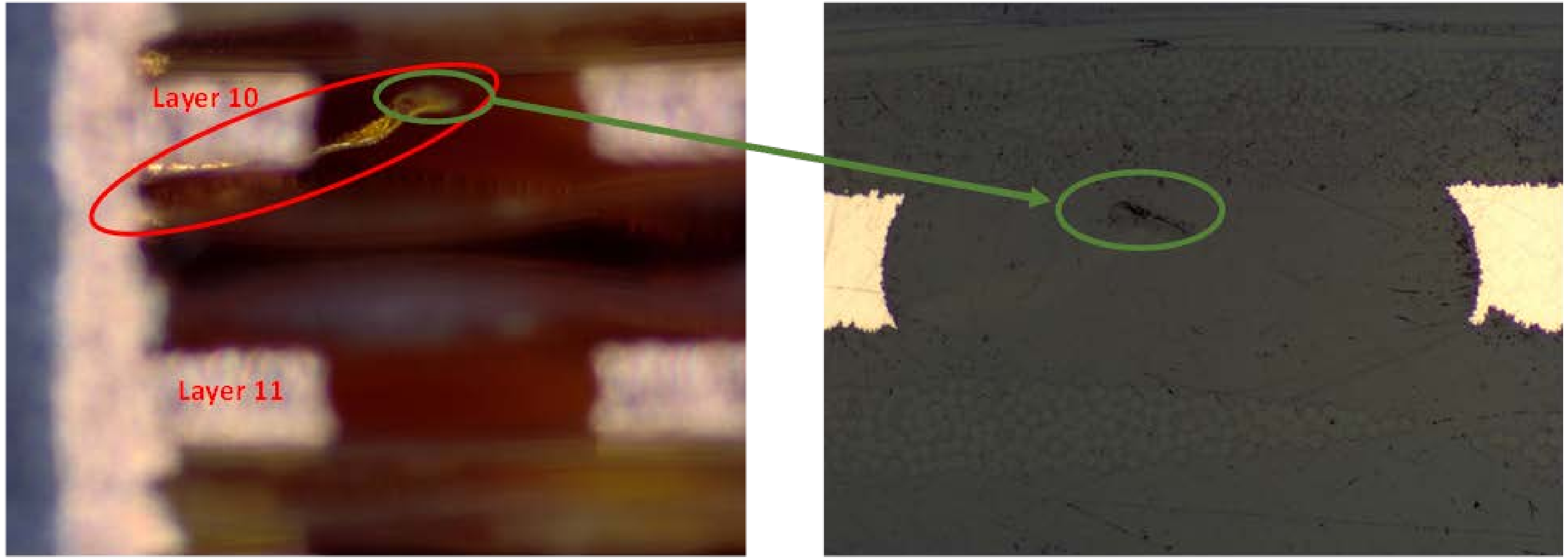
- Failure mechanism of the PWA2 has been determined to be a defect in the PCB. This conclusion is based on a number of investigation steps, including the sectioning of the three microsection coupons removed from the failed PWA2, and the findings discovered during the re-inspection of the panel 070 conformance coupons.
- As a result of the failure analysis, evidence led the team to the conclusion that the mechanism causing the failure of the CS within the CSA is a foreign inclusion, which acted as a catalyst in propagating a crack, thereby providing a pathway for copper plating and plating residue to travel up the crack.
- This condition reduced the design clearance distance between a buried via (which is signal GND) and layer 11 plane (which is a 3.3V plane). This reduced distance had been breached by a conductive filament growth facilitated by plating residue over time.

Failure Analysis Root Cause

- The filament that breached the reduced clearance between the ground buried via and the power plane is CAF (Conductive Anodic Filament) facilitated by plating residues. CAF is an electrochemical process involving the transport of a metal through, or across, a nonmetallic medium under the influence of an applied electric field.
- A filament formed from the end of the foreign inclusion from the ground buried via to the power plane (P3.3V). This resulted from the combination of electrical bias (P3.3V and GND), plating residues, moisture (RH {relative humidity}) and time.

Evidence Supporting the Root Cause

- An independent review of a control mount from the failed PWA2 panel 070, under dark field (left photo), indicated inclusions violating IPC 4101 requirements. Inclusion was determined to be copper.



Dark Field

Bright Field

Evidence Supporting the Root Cause

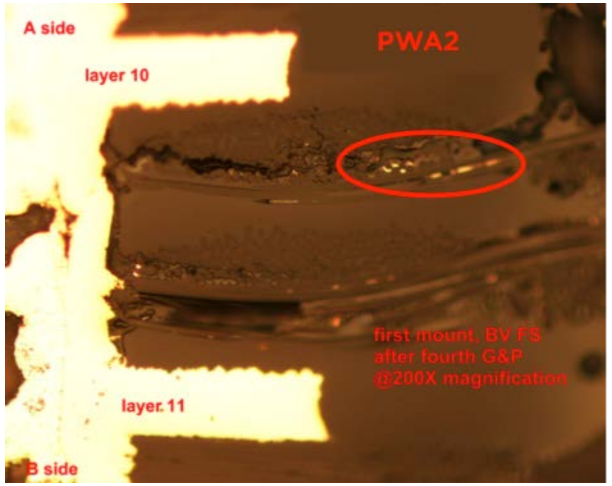
- An independent review of one of two control mounts from the failed PWA2, was determined to be a resin-rich, crack-like inclusion.

Dark Field

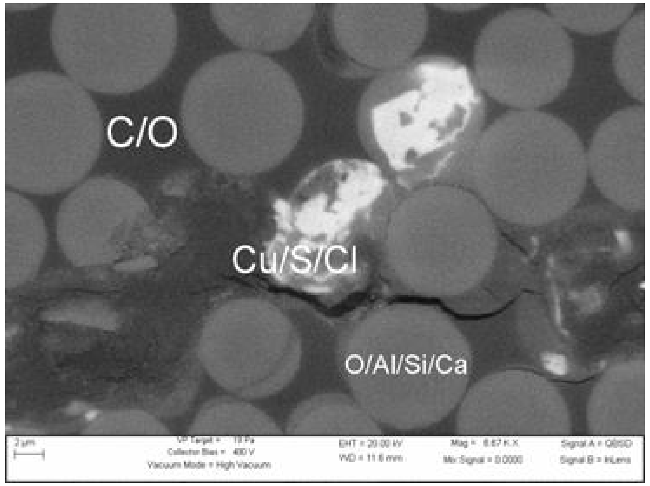
Bright Field

Evidence Supporting the Root Cause

- Sectioning of the failure site revealed copper within the fiber bundles, along with chlorine and sulfur that we believe to be a result of copper-plating residues. The mechanism that accounts for all three elements is a defect in the resin (inclusion with a crack) that allowed for the wicking of the plating solution.



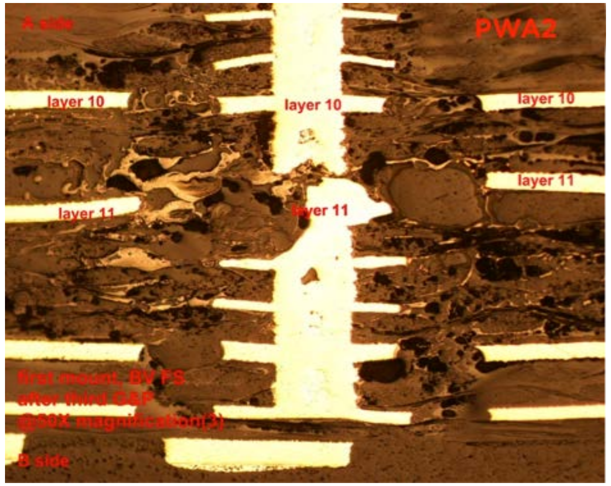
Dark Field



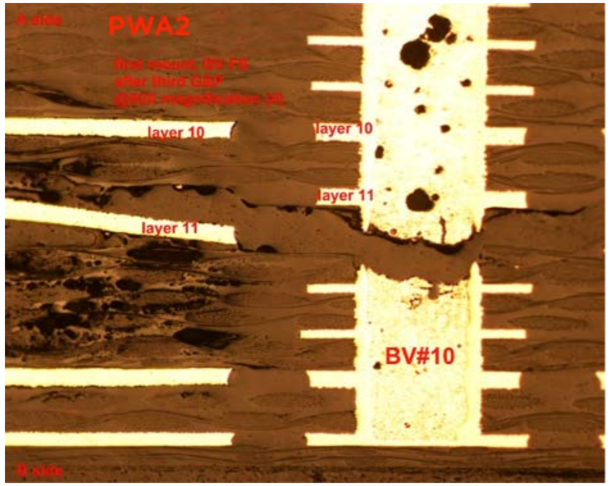
SEM EDS

Evidence Supporting the Root Cause

- Failure site mount shows epicenter of the failure as a buried via (signal Ground) left photo. Shows melted copper and melted conductive fill material. Other buried vias show complete separation but no melting.



Failure site Dark Field



Blind Via Dark Field

Proposed Corrective Actions

- Add dark field inspection requirements
- Require CS burnin hours
- Flow down cleanliness requirements to approved suppliers for lamination booking
- Consider PCB material change to multi-functional epoxy
- Tighten supplier controls on inner layer AOI rework

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