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Conformal Coating Value/Risk Assessment for Sandia Satellite Programs

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ABSTRACT

Conformal coatings are used in space applications on printed circuit board (PCB) assemblies primarily as a protective barrier against environmental contaminants. Such coatings have been used at Sandia for decades in satellite applications including the GPS satellite program. Recently, the value of conformal coating has been questioned because it is time consuming (requiring a 5-6 week schedule allowance) and delays due to difficulty of repairs and rework performed afterward are troublesome. In an effort to find opportunities where assembly time can be reduced, a review of the literature as well as discussions with satellite engineers both within and external to Sandia regarding the value of conformal coating was performed. Several sources on the value of conformal coating, the functions it performs, and on whether coatings are necessary and should be used at all were found, though nearly all were based on anecdotal information. The first section of this report, titled "Conformal Coating for Space Applications", summarizes the results of an initial risk-value assessment of the conformal coating process for Sandia satellite programs based on information gathered.

In the process of collecting information to perform the assessment, it was necessary to obtain a comprehensive understanding of the entire satellite box assembly process. A production time-line was constructed and is presented in the second section of this report, titled "Satellite Box Assembly", specifically to identify potential sources of time delays, manufacturing issues, and component failures related to the conformal coating process in relation to the box assembly. The time-line also allows for identification of production issues that were anecdotally attributed to the conformal coating but actually were associated with other production steps in the box assembly process. It was constructed largely in consultation with GPS program engineers with empirical knowledge of times required to complete the production steps, and who are familiar with associated risks from activities such as handling, assembly, transportation, testing, and integration into a space vehicle (SV) system.

Finally, section three titled, "Summary and Recommendations for Future Work", briefly summarizes what we have learned and describes proposed future work.

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SECTION 1: CONFORMAL COATING FOR SPACE APPLICATIONS

I. Benefits

The primary purpose for conformal coating of PWB assemblies in space applications is the protection of electronic assemblies from environmental contaminants including particles, dust, dirt, moisture, corrosive vapors, and fungus[1,2,3]. Many electronic assemblies are tightly packed with components, thus having small spaces between conductors (e.g., solder pads and leads). First, particles, that settle onto electronic modules during production, ground testing, and launch or buoyant particles in the zero-gravity space environment on orbit that contact and span two or more closely spaced conductors may result in a short circuit, leading to potentially serious electrical failures in the satellite system. Despite efforts to keep satellite assemblies clean and free from contaminants, the possibility that stray particles, metal shavings, dust, and dirt will be present exists. Conformal coating provides a layer of electrical insulation preventing contact between physical contaminants and conductive features on PCB modules. Second, moisture and corrosive vapors over time may result in corrosion of metals in PCB assemblies. Though conformal coatings are not hermetic and thus do not seal electronics from moisture and solvent vapors, they do act as barriers to slow diffusion of moisture and corrosive vapors through the polymer before reaching electronics. Third, biological contaminants such as fungus may also lead to degradation of PWB assemblies, conformal coatings help to protect electronics from biological contaminants.

Other benefits of conformal coating electronic assemblies include structural integrity and the mitigation of tin whiskers, as discussed below.

Structural integrity: Conformal coatings are required to adhere to all the surfaces of PWB assemblies to which they are applied, and must have sufficient mechanical properties (e.g., modulus) to be structurally sound and provide reasonable abrasion resistance. It seems intuitive that a conformal coating applied over electronic components on PCBs may provide some structural integrity and protection for solder joint connections against mechanical shock and vibration. While studies have been performed to determine the contribution of conformal coating to solder joint reliability in extreme environments such as thermal cycling and shock/vibration, the results are coflicting.

Hillman, et.al.[6], (Rockwell Collins) performed thermal cycling experiments of Ball Grid Array (BGA) assemblies that had no conformal coating along with BGA assemblies that were coated with acrylic and parylene conformal coatings. Test results showed the conformal coatings provided no significant improvement in solder joint reliability. Qi, et. al.[7], performed thermal cycling and combined thermal cycling and shock/vibration of BGAs that had been coated with Humiseal 2A64 polyurethane coating applied in two different ways (spray and dip). Results showed that the coating application process (spray or dip) had little influence on failure data due to thermal cycling from -50^{o}C to 150^{o}C and vibration stress levels of 0.045 G2/Hz and 0.10 G2/Hz over a frequency range of 100 to 1000Hz. However, Darren, et. al.[8], discovered one combination of epoxy and parylene coating that appeared to improve the reliability of chip-on-board electronic structures, while other coating combinations provided no significant benefit. Blanche (NASA, Marshall Space Flight Center) has observed that conformal coating may provide an incidental benefit of structural integrity to solder joints in PWB assemblies, but it is a marginal benefit [9]. Blanche recommends the structural integrity of electronics be derived from good PWB design and appropriate use of component staking and underfill and not from conformal coating.

Due to lack of data supporting a coating contribution to structural integrity and reliability of solder joints, it should not be considered a function of conformal coatings, though in some cases they may provide some marginal benefit.

Tin whisker mitigation: Tin whiskers are elongated thread-like protrusions of tin that have been observed growing on surfaces of pure tin in the electronics industry. While tin whisker formation is not fully understood, it is generally accepted that residual stresses in the metal increase the likelihood of tin whisker formation[10-16]. According to NASA, there are a number of partial and complete losses of military and commercial satellites that are known or suspected to be caused by tin whiskers or other metal whiskers[17]. For example, tin whiskers were determined to be the cause of the loss of a commercial spacecraft in 1998 [10,11]. A significant amount of study has been done to determine the cause of tin whiskers and to mitigate their formation. One study to investigate the potential for conformal coatings in mitigating tin whisker growth by Woodrow and Ledbury[12] tested six different coatings and found coatings generally suppress tin whisker formation. Whiskers eventually grew under 50°C/50% RH conditions but did not penetrate thicker coatings (3.9-6.0 mils). Parylene was most successful, and non-crosslinked acrylic was worst at suppressing tin whiskers, however, none of the coatings completely stopped tin whiskers from forming. In additional work, Woodrow[13] documented that conformal coatings helped to suppress tin whisker formation as compared to uncoated controls during 401 days of ambient exposure, however, during 347 days of additional humidity controlled exposure (25°C/97% RH), tin whiskers penetrated all conformal coatings regardless of thickness. Kadesh and Brusse[11] performed a study of Uralane 5750 polyurethane coating commonly used in space applications to determine its effect on tin whisker growth. The conformal coating appeared to slow the formation of tin whiskers compared to uncoated specimens. Whiskers growing under the coating were about 0.05 mm long while the longest whisker on an uncoated specimen was 2 mm long (0.13 mm/year average growth rate). Whiskers penetrated thin areas of coating (~0.25 mm thick) but not 2 mil thick areas.

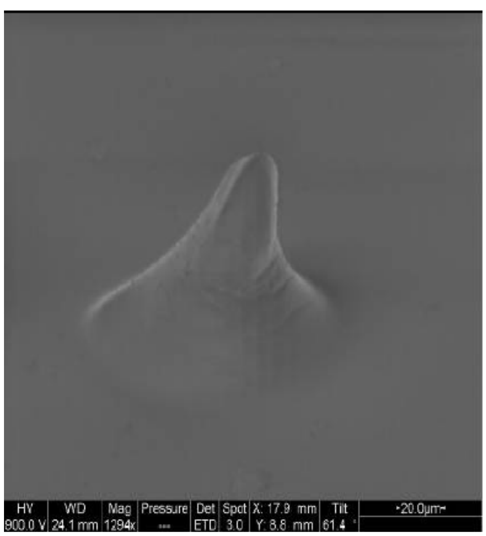
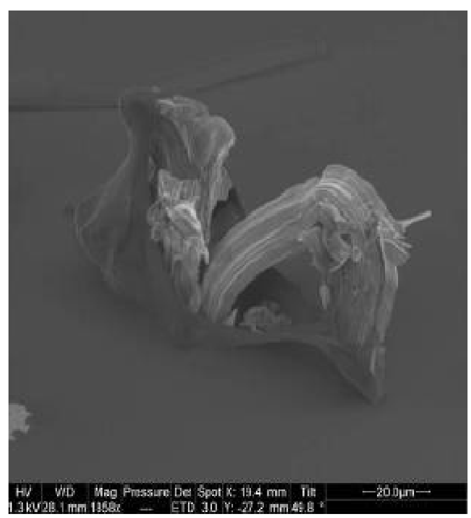
An additional benefit of conformal coating in terms of tin whisker mitigation is that coatings serve as a dielectric layer to protect electronics from tin whiskers that have penetrated the coating. In the event that a penetrated whisker breaks off, rather than contacting electrical components, solder joints, or traces, the whisker would contact the coating. The conformal coating would protect the electronics from electrical shorting provided that the potential difference between the electronic components and the tin whisker does not exceed the dielectric breakdown strength of the coating[10].

The work summarized here demonstrates conformal coating may retard the growth of tin whiskers under certain conditions and can protect electronics from whiskers that penetrate the coating; however, conformal coatings are not the cure for tin whiskers. Examples of tin whisker formation with and without conformal coating are shown in Figure 1. Tin whiskers can and do grow under coatings and may actually penetrate them.

It is clear from the literature that conformal coatings do not eliminate tin whiskers, and other mitigation methods should be used to avoid them. This may be done by elimination of pure tin and other pure metals known to grow metal whiskers, or by coating pure tin with eutectic (e.g., tin/lead) solders or with tin/bismuth coating[14].

Figure 1: Tin Whiskers and Conformal Coat Mitigation

(http://nepp.nasa.gov/WHISKER/reference/tech_papers/2007-brusse-metal-whiskers.pdf)

 (a). Tin whiskers on a plated ceramic chip capacitor – no conformal coating.	 (b). Nodules formed under 2 mils of Uralane 5750 conformal coating after 9 years in ambient conditions.
 (c). Whisker formed and lifting 0.5 mils of Uralane (same conditions as b).	 (d). Whisker formed and breaking thru 0.1 mils of Uralane (same conditions as b).

II. Types of Conformal Coatings

There are five primary types of conformal coating materials used for environmental protection of electronics: acrylics, silicones, polyurethanes, epoxies, and parylenes. The first four are typically applied with spray or dip operations, while parylenes are applied using a vacuum deposition process. Proper selection of conformal coating material may increase lifetimes and improve performance of electronic assemblies[1].

Several coatings of each type are commercially available[18]. Information below from suppliers and users of conformal coatings demonstrate the advantages and disadvantages of each type.

Acrylic (Type AR): Acrylics[1,3,19,20] tend to the easiest of the coatings to process and apply. They are also relatively easy to repair. Moisture resistance of acrylics is comparable to that of silicone and polyurethane, but they generally have poor resistance to petroleum solvents and alcohols. The dielectric strength of acrylic coating is approximately 1500 volts/mil and the temperature range for acrylic coatings is approximately -59^{o}C to 132^{o}C.

Advantages:

- Relatively easy to apply and repair (using chlorinated solvents)
- Cures in minutes
- Good electrical and mechanical properties
- Long pot-life with little shrinkage and little or no exotherm during cure which is desirable to avoid damaging heat-sensitive components

Disadvantages:

- Solvent sensitivity (particularly to chlorinated solvents, which are used to remove and repair acrylic coatings)

Silicone (Type SR): Due to their flexibility, silicone coatings[1,3,19,20] tend to have good shock resistance. They are generally easy to apply. Spot repairs of silicone can be done mechanically, but overall removal can be difficult due to solvent and heat resistance of the material. Dielectric strength is approximately 1100 volts/mil, which is somewhat less than other coatings, but the flexibility of silicone allows for application of thicker coatings. The temperature range of silicones is about -65^{o}C to 200^{o}C.

Advantages:

- Useful for higher temperature applications up to 200^{o}C (392^{o}F)
- Excellent humidity and corrosion resistance
- Good thermal endurance, which is good for high thermal dissipating components (e.g., power resistors)

Disadvantages:

- Limited pot-life
- High coefficient of thermal expansion (CTE)
- Difficult to repair due to solvent and heat resistance (but can be mechanically removed)

Polyurethane (Type UR): Polyurethane coatings[1,3,19,20] tend to be hard and durable, and provide excellent abrasion and solvent resistance. Moisture resistance is similar to that of acrylic and silicone. Relative hardness of coating and cure shrinkage may stress components. Rework of urethane coatings in localized regions can be done by thermally softening the material, but removal of large areas is extremely difficult. The temperature range of polyurethane coatings is approximately -59^{o}C to 132^{o}C. Dielectric strength is in the range of 1500-2500 volts/mil.

Advantages:

- Available as one-part or two-part systems
- Excellent humidity and chemical resistance
- Outstanding dielectric properties for extended periods of time

Disadvantages:

- Rework and repair can be difficult and time consuming due to chemical resistance (but localized reworking can be done with thermal softening)
- Require close control of humidity during application – sensitivity to moisture during cure can cause vessication (blistering) under humid conditions which can lead to circuit failure

Epoxy (Type ER): Epoxy coatings[1,3,19,20] usually consist of a two-part thermosetting system. They provide excellent resistance to moisture and solvents. The temperature range of epoxies is approximately the same as polyurethanes. Coatings tend to be hard, and cure shrinkage may stress components. Repair of epoxy coatings is difficult, and must be burned through in localized areas. Removal over large areas is nearly impossible.

Advantages:

- Excellent humidity and chemical resistance
- High abrasion resistance

Disadvantages:

- Inherently short pot-life
- Extremely difficult to remove and repair chemically – chemicals that attack epoxy conformal coatings also attack epoxy boards and components (repairs must be made by burning through the coating)

Parylenes (Type XY): Parylene coatings[21-24] (also called poly-para-xylylene) are applied by a chemical vapor deposition process where the polymer is vaporized into small segments (i.e., dimers) and then pyrolized into a monomer as it enters a vacuum chamber containing an assembly for coating. The monomer simultaneously adsorbs and polymerizes on the substrate in a very uniform manner. Parylene coating is fairly thin compared to the other coatings, generally less than 2 mils in thickness. There are three different types of parylene coatings (Parylene N, C, and D), which vary somewhat in chemical structure and properties. Parylenes have very high dielectric strength (5500-7000 volts/mil), and are very resistant to solvents. Parylene is significantly more expensive than conventional coatings and it is very difficult to remove.

Advantages:

- Exceptional environmental protection and corrosion resistance
- Excellent dielectric strength due to the ability of parylene to adhere and conform to all surfaces
- Vacuum deposition is very uniform and avoids thin-out, pinholes, run-off and sagging that can occur with spray and dip techniques

Disadvantages:

- More expensive than spray or dip coating techniques
- Requires special equipment (vacuum chamber for parylene deposition)
- Very difficult to remove parylenes – requires techniques such as plasma etching or micro-blast abrasion

The 5 different types of conformal coatings have a range of properties, each with advantages and disadvantages. Thermal, electrical, and mechanical properties, ease of application and removal are among the properties that should be considered in selecting a conformal coating. Properties and specifications of conformal coatings are available from material suppliers.

III. Risks of Using Conformal Coating

Are there risks inherent to conformal coating PCBs that may outweigh the benefits? Perceived risks include: 1) Mechanical damage of electrical assemblies and electrical damage due to electrostatic discharge (ESD) incurred during handling; 2) Electrical failures due to stresses induced by the coating on solder joints. To understand the reality of these risks, we monitored the current coating process to identify sources of failures.

In June 2007, we visited GTC Corporation in Albuquerque to observe the conformal coating process used for Sandia's satellite assemblies. PCB handling and subsequent staking, masking, and coating of assemblies were observed. GTC personnel handled the assemblies carefully at all times to avoid mechanical damage. Workers were electrically grounded during handling, staking, masking, and coating of the assemblies to avoid ESD damage to electronics. The actual coating of the assemblies with Hysol PC18M using a spray nozzle in a spray hood did not appear to introduce any significant risk of mechanical or electrical damage to the assemblies. The visit resulted in no obvious problems with the conformal coating process that would result in mechanical or electrical damage to satellite modules.

In addition to the GTC visit, failure report information was gathered from the failure report database on the Org. 5761 website to determine whether or not failures may be related to conformal coatings. In June 2007, approximately 700 GPS related failure reports (i.e., using key words GPS, BDP, BDY, NAP) were found in the database. While most failure descriptions were not specific or were inconclusive, it was found that about 2.3% of the GPS assembly failures were potentially related to the conformal coating process. The remaining failures were due to other causes including design problems, assembly and handling errors, and manufacturer defects. For example, about 13% of the failure reports described assembly/installation issues of components on PCBs. Based on this analysis, only a small fraction of the problems encountered with satellite electronics were due to the conformal coating process.

One well-known risk regarding conformal coatings is the potential for stresses to be induced by the coating on electronic components during thermal cycling. This is especially true if the coating is very thick (> 5 mils for many coatings) and if there is a significant coefficient of thermal expansion (CTE) mismatch between the coating and the substrate materials being coated. For example, glass diodes in electronic assemblies may crack when stress is induced on the diode by a thick conformal coating. Regarding scenarios such as this, NASA in their "Workmanship Standard for Staking and Conformal Coating of Printed Wiring Boards and Electronic Assemblies"[25] specifies thickness tolerances for the different types of conformal coatings. The NASA recommendation for conformal coating thickness is shown in Table 1. James Blanche (NASA, Marshall Space Flight Center) explained NASA's experience as, "component damage from cured conformal coatings is reduced when coatings are applied within the specified thickness tolerances"[9].

Table 1: Conformal Coating Thickness tolerances from NASA Technical Standard NASA-STD-8739.1

Type of Coating	**Cured Coating Thickness (in)**
Acrylic	0.001 to 0.005
Urethane	0.001 to 0.005
Epoxy	0.001 to 0.005
Silicone	0.002 to 0.008
Parylene	0.0005 to 0.002

While there are risks involved in conformal coating electronic assemblies, they can be mitigated. The majority of risk is associated with general handling, transport, and processing of PCBs, factors that are present in other production processes and are not specific to conformal coating. Appropriate handling, electrical grounding, packaging, and transport of assemblies before, during, and after coating will help to prevent mechanical and electrical damage to PCB assemblies. Applying conformal coating at a thickness within a recommended range will avoid undue stresses that may cause damage to components and assemblies.

IV. Hysol PC18M Conformal Coating Specific to GPS Satellite Programs

The conformal coating used for the GPS satellite program is Hysol PC18M [26] (Henkel Corp.), which is a one-part polyurethane (Type UR) coating that is diluted with toluene and sprayed on to assemblies in 2 coats on both sides of assemblies, resulting in a coating thickness of about 5 mils (0.005 inches). PC18M has been used throughout the life of the GPS program. It passes outgassing requirements for space applications when moisture and volatiles are properly baked out, and the coating is reasonably removable for repairs or rework on the underlying electronics (in the event of a repair, the region is recoated manually using a brush).

From the technical literature and from consultation with other space programs (e.g., NASA, Lockheed Martin), we discovered that one coating widely used in similar applications to ours is Uralane 5750 (also called Arathane 5750), available from Huntsman Corporation.

The present-day process of conformal coating PCBs with PC18M consists of 15 steps, as described below:

1. A readiness review is conducted by Sandia engineers to insure that electronic modules and motherboards have been properly designed and assembled, and all transportation documentation is in order for the conformal coating process to begin.

2. A visual mechanical inspection is performed to identify and repair defects such as broken or improperly installed components before modules are transported for conformal coating. This pre-coating inspection is described in specification MSTC-PS 06-003 [27].

3. Modules are transported to the coating facility (e.g., GTC Corp.) by Sandia personnel. They are packaged in anti-static bags to avoid ESD damage, and are transported in lined carry boxes to avoid mechanical shock/vibration damage.

4. A visual inspection of the electronic modules is performed when they arrive at the coating facility to ensure they were not damaged during transport.

5. Modules are cleaned with ethyl alcohol and isopropanol, which are brushed and sprayed on the surfaces. Dry nitrogen is used to blow dry excess solvents, and then the units are placed in an oven at 66^{o}C (150.8^{o}F) for 24 hours or 80^{o}C (176^{o}F) for 18 hours to remove residual solvents.

6. A cleanliness test is performed to insure that the modules have been properly cleaned.

7. Components are staked where required using 3M® EC-2216 epoxy adhesive. Depending on the application, the EC-2216 adhesive may be filled with Cab-

o-Sil® fumed silica filler to increase viscosity. Staking is allowed to air dry until it is tack-free.

8. The areas of modules that are not to be conformal coated are masked. Masked areas include open connectors, locations where components will be placed after coating (the coating will subsequently be brushed on), and locations where mechanical hardware to fasten modules into the satellite boxes will be attached. Except in these described cases, coating is applied to all electrically functional areas of modules (though coating cannot be applied under ball grid arrays (BGAs) or column grid arrays (CGAs) which are not accessible).

9. Modules are warmed in an oven in preparation for conformal coating.

10. Spray coating of Hysol PC18M is performed in four directions to coat around all sides of components on modules. There are two coats applied in this manner on each of the two flat module sides.

11. An overnight air cure is performed, followed by removal of the masks.

12. The coated modules are baked out for 16 hours at 50^{o}C in an oven.

13. A detailed post-coating inspection is performed at the coating facility to observe staking or coating defects, also mechanical damage to components on modules.

14. The coated modules are vacuum baked for 24 hours to remove residual volatiles. This step ensures the conformal coating material will meet the outgassing requirements in NASA SP-R-0022A[4].

15. The conformal coated modules are returned to Sandia engineers. As with the initial transport, they are packaged in anti-static bags to avoid ESD damage, and are transported in lined carry boxes to avoid mechanical shock/vibration damage.

In the event of inadvertent damage to modules during the coating process, Sandia engineers work in collaboration with the coating contractor work to perform repairs and ensure the modules are operational and on schedule.

SECTION 2: SATELLITE BOX ASSEMBLY

I. Conformal Coating in the Production of Satellite Box Assemblies

Conformal coating of electronic modules is just one of numerous processing and production steps that result in the successful manufacturing, qualification, and fielding of a GPS satellite box assembly in a system that is subsequently integrated into a space vehicle (SV) for launch. Obviously, in a production process that contains a significant number of individual processes of varying complexities, appropriate coordination of the many production steps performed by a considerable number of electrical and mechanical engineers, technologists, and contractors is critical to providing a functional and reliable satellite box assembly in a timely fashion. Even with good coordination of the production process, the total time required to assemble satellite box assemblies for flight systems is significant.

To document the amount of time required to fabricate a satellite box assembly, a box assembly production timeline has been constructed which indicates the major production processes that occur and the approximate time required for each process. The time necessary to complete most of the production processes may vary somewhat and cannot be precisely determined, so a time range is specified. Satellite box production time can fluctuate because satellite box assembly designs may vary in size, functionality, and complexity, some requiring more production and processing time than others. Time required for manufacturing, processing, and testing may also differ depending on the amount of tuning, component replacement, and repair that is required in specific situations.

There are a number of specifications currently in place that document process requirements for many of the production steps in the assembly of flight hardware, including conformal coating. Requirements for various processes including Components, Fabrication, and Repair (CFR) quality assurance processes[28], bare printed circuit board fabrication[29], PWB module fabrication[30], procurement requirements for electrical parts[31], conformal coating requirements[32], and pre- and post-conformal coating inspection[27] can be found in individual specifications for additional information.

II. Satellite Box Assembly Timeline

Based on past experience of engineers and supporting personnel in assembling satellite boxes for the GPS program, a GPS satellite box assembly process flow timeline has been constructed and is shown in Figure 2. The time required for the various processing steps are generally expressed in ranges of time because, as was previously mentioned, fabrication time can vary depending on a number of factors including the complexity and size of the assembly, time required for component procurement, and the type and number of production issues (e.g., electrical and mechanical failures) that are encountered. The GPS satellite box production steps are described in greater detail below including potential risks of production issues and some ways that the risks are mitigated.

Most of the production steps involve handling, assembly, and/or testing of components, modules, and systems. These types of operations present the potential risks of electrical failures such as electrostatic discharge (ESD) of static sensitive parts and electrical overstress (EOS) of components, mechanical damage due to mishandling such as bumping or dropping an assembly, and contamination of assemblies from dirt, dust, particles, skin oils, etc. Proper handling, assembly, and testing techniques should be employed to mitigate the risks of electrical and mechanical damage and contamination. These include (but are not limited to) appropriate use of anti-static packaging handling equipment to avoid ESD, following established test procedures to mitigate EOS during testing, proper packing during handling and transport to avoid mechanical damage, and use of gloves and protective bags to avoid contamination.

Component procurement: Components are procured from various suppliers. There is a risk of procuring incorrect parts, either through incorrect design specification, ordering, or through suppliers providing incorrect parts. Component acceptance procedures below are used to identify incorrect parts that are inadvertently received. Components may be procured in as little as 1 week, or it may take 26 weeks or more. A typical time frame for component procurement is 8-10 weeks.

It should be noted that there is a significant amount of preliminary work that must be done prior to component procurement to determine what components will be required for the satellite system. A concept of operations, system requirements and design (including environments), subsystems requirements and design, and module requirements and design must be established before components procurement and subsequent steps can proceed.

Component Acceptance: Components must meet various mechanical, electrical, and rad hardness requirements. Prohibited materials (e.g., pure tin, cadmium plated, selenium, zinc) must be avoided. These metals are capable of forming metal whiskers which can cause short circuits if they come in contact with conductors in electronic assemblies. For example, tin whisker formation[10-16] is possible with uncoated pure tin leads. XRF analysis is done on samples in each lot of parts received to screen out prohibited materials. Destructive Physical Analysis (DPA) is also performed on samples from all new procurement lots received, except passive parts and connectors; however these component types do require Prohibited Material screening. Improper packaging of components shipped from a supplier to Sandia and from Sandia to the fabrication facility has occurred, which presents a risk of damage to parts. Parts must be appropriately packaged to avoid shipping damage. Component acceptance will typically take from 1 to 3 weeks, depending on how quickly DPA is completed.

Component Kitting: Component kitting is the process of placing appropriate components into individual kits for module fabrication. Kitting takes approximately 1 week to complete, provided that all required components are in stock. There is a risk of incorrect components being placed into module kits. Care must be taken by component handlers to insure that the correct components are placed into component kits. Mechanical damage (i.e., bent leads) has occurred during shipping to the fabrication facility due to improper packaging. Fabrication facilities include Aeroflex Corp., GTC, L&L, and Goodrich.

Module Fabrication: Module board and motherboard fabrication is included in this step. Module fabrication can take from 2 to 8 weeks depending on the PWB fabricator, but an average fabrication time is 6 weeks. Significant PWB fabrication issues include design complexity (e.g., board layers, density), production schedule, and cost. Board designs have become much more complex, with more potential for problems and failures. Risks associated with module fabrication including electrical short circuits and open circuits are mitigated by the addition of Highly Accelerated Thermal Shock (HATS) testing on PWB designs that meet specific design feature criteria. Currently, no requirements exist for passing HATS testing as the gateway to assembly for GBD IIF. At this time, HATS testing is for informational purposes only.

Housing Fabrication: In this step, the housing for the box assembly is fabricated. Housing fabrication is a multi-step process which includes procurement of the housing materials, machining, assembly, soldering, and alignment of the housing. The entire process takes approximately 5 months to complete. Housing fabrication is performed in parallel with other box assembly production steps including module fabrication, module assembly, and module testing. Lubricating oils are used in the machining of metals, and metal shavings and particles are generated during the machining process. Oils, metal shavings, and particles are contaminants that could damage to electronic components and PWBs and must be removed.

Module Assembly: Modules are assembled by soldering components on to PWBs. The time required for module assembly can vary with module size and complexity; however the average assembly time is 6 weeks from the time that all components are available. The potential exists for assembly errors. Assembly errors include installing parts in the wrong orientation, installing incorrect parts, and parts being damaged during installation. Risk of assembly errors is mitigated by performing Flying probe In Circuit Testing (ICT) on assemblies to test for shorts, open circuits, correct component value and component orientation. As with any testing that is performed on modules or systems, there is a risk of mechanical or electrical damage, and contamination from ICT and care must be taken during testing to avoid these problems. However, ICT testing is necessary to identify possible module assembly errors before proceeding to subsequent steps.

Module Test: A module test is performed at Sandia at ambient temperature and from temperatures of -40^{o}C to 80^{o}C. Module testing can take up to 12 weeks to complete. Analog testing takes up to 12 weeks, power supply testing requires 6 to 8 weeks, and digital testing takes 4 weeks, with the various types of testing being done in parallel. Engineer probing during troubleshooting has also been found to cause damage to both components and bare boards when not done properly. Proper handling, grounding, and testing techniques should be used to avoid damage of modules during testing.

Box Assembly: The box assembly step includes installation of the motherboard into the box housing, secondary wiring or other secondary assembly operations on the motherboard, and installation of modules into the box housing. Box assembly typically takes about 6 weeks.

Box Test: This is a fully functional test of the box assembly with thermal cycling. Box testing requires approximately 8 weeks for completion. There is a potential for functional, ESD or EOS failure that would then necessitate repair. Functional failure is component infant mortality failure not caused by ESD or EOS.

Initial System Test: This is an initial test of multiple box assemblies linked together in a functional system, and takes place in a general electronics lab environment with established test procedures. The initial system test is done in about 1 week for a mature GPS system design. For a new system, the initial system test could be significantly longer (e.g., multiple weeks) in duration.

Box Characterization: Box characterization is an assessment of its initial functional performance. The characterization is completed in about 4 weeks.

Box Disassembly: Modules are removed from the box assembly in preparation for conformal coating. Box disassembly is done in about 2 days. Preparation of the motherboard in the box housing is also done prior to conformal coating. For the GPS program, motherboards are typically not removed from box housings for coating.

Pre-Conformal Coating Module Inspection and Repair: A visual inspection of modules and the motherboard is performed after box disassembly and prior to conformal coating. The inspection and repair is completed in about 1 to 2 weeks. It has been found from past experience during conformal coat pre-inspection that repairs are needed on up to 50% of modules. There is a risk of missing a damaged component on a module that could be put through to conformal coating. If a damaged component is discovered after conformal coating, the coating must be removed from the region of the component, the component must be replaced, and the coating must be reapplied with a brush-on technique. Care must be taken when repairing or replacing damaged components because there is a risk that other components could be damaged in the process.

Module Conformal Coat: This includes all required steps for conformal coating of modules (readiness review, module inspection, transport to the coating facility (e.g., GTC), cleaning, staking, tacking, masking, coating, curing, bake-out, post-coat inspection, thermal vacuum to remove volatiles, and delivery to engineers). This entire process for all modules in a box assembly typically takes 5 to 6 weeks to complete. An individual module that is given high priority can be completed in about 5 days. Proper cleaning of modules (and keeping them clean prior to coating) is essential to promote good adhesion of conformal coating and avoid delamination from surfaces. There is a possibility of mechanical damage during all of the process steps related to conformal coating. There is also a risk of ESD damage during these processes, but grounding and other appropriate measures are employed to avoid ESD. It was proposed that the designs of about 50% of module assemblies are stable and could be conformal coated immediately after initial assembly, prior to the initial delivery to Engineering. Conformal coating after initial assembly would only be appropriate for modules meeting certain criteria (e.g., no Actels). Electrical engineers with the GPS program have commented that electrical repairs are much more complicated and take significantly longer to complete after conformal coating has been applied due to necessity to remove coating in the region of the repair. If conformal coating is applied before assembly errors have been identified, significant delays could occur due to need to selectively remove the coating, especially in situations where large numbers of components need to be repaired, replaced, or reoriented.

A new process of recording digital images of completed modules has been instituted by other Satellite programs and is being considered for GPS. This process takes approximately 1 day for all modules.

Box Reassembly: After modules are returned from conformal coating, they are reassembled into the box housing. The box reassembly takes approximately 2 days.

Box Functional Test: A functional test is performed after the box reassembly. The functional test is completed in about 1 week.

Primary System Test: This step involves the testing of the entire system which consists of multiple box assemblies. The primary system test takes approximately 1 to 4 weeks to complete.

Box Assembly Close-out Vibration/Shock Test: This is the final vibration/shock test for the box assembly. Testing time is about 2 weeks. There is the possibility of mechanical damage during vibration/shock testing.

System Test: The final system test is performed at Sandia prior to shipping to the contractor. The system test is typically done in 1 week. The possibility of ESD and EOS failures exist during this testing.

Readiness Pre-Thermal Vacuum: Preparation for thermal vacuum testing is done in this step. This preparation is completed in about 1 week.

Thermal Vacuum Test: Thermal vacuum (TVAC) testing of the system is intended to replicate the space environment. Testing is typically completed in about 2 weeks. There is a risk of electrical failures during thermal vacuum testing. There is also a risk of thermal overstress which should normally be mitigated by using proper test procedures during TVAC.

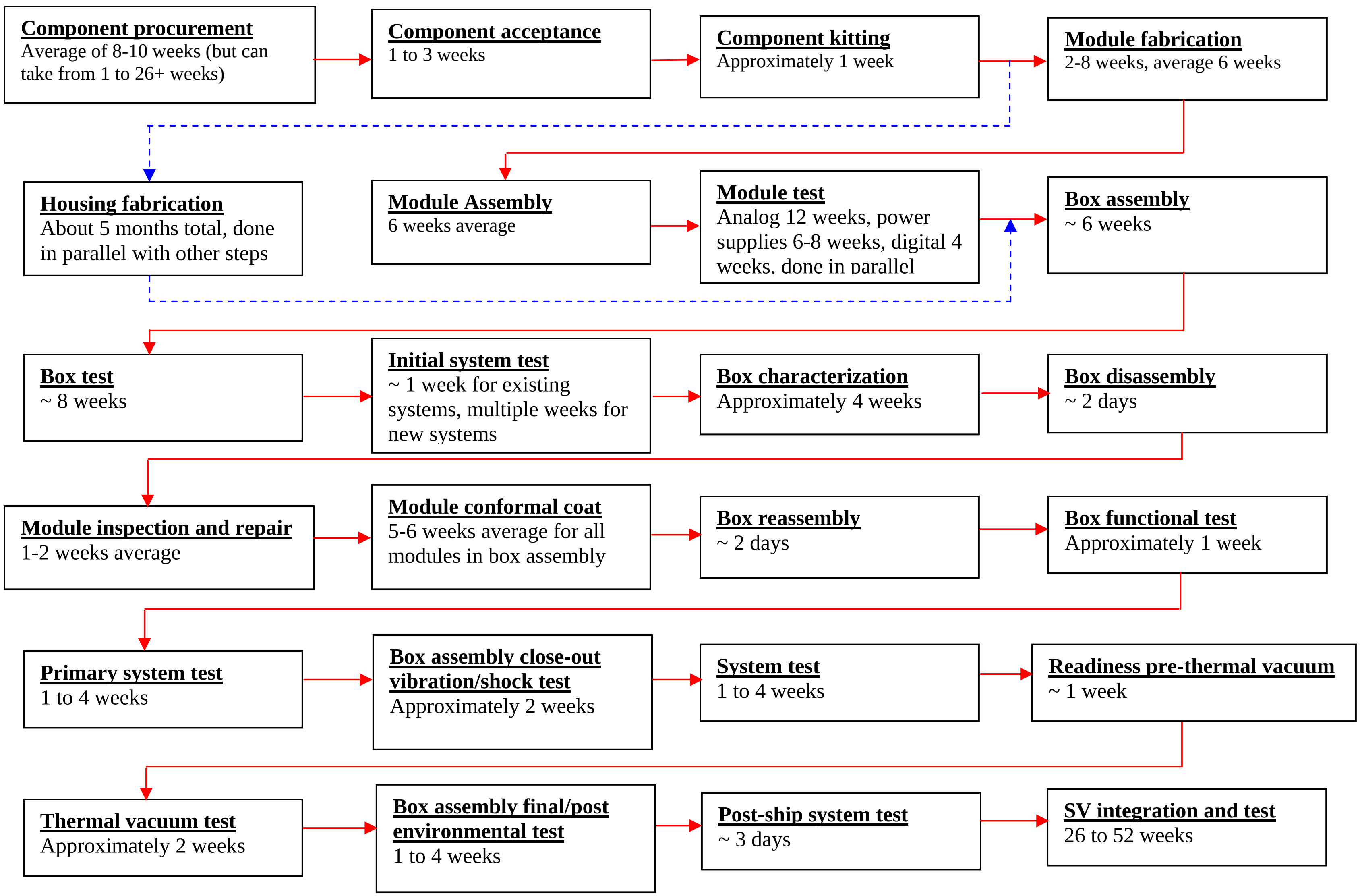
Box Assembly Final/Post Environmental Test: This is the final testing of the box assembly that is conducted after the thermal vacuum environment test. Testing can take from 1 to 4 weeks to complete.

Post-Ship System Test: A system test is performed after shipping to the contractor. The system test is typically completed in about 3 days. There is the possibility that mechanical damage could occur during shipping. There is also a risk of ESD and EOS failures during the post-ship system test.

SV Integration and Test: The satellite system is integrated into the space vehicle (SV) and then tested. Testing is performed by Sandia at the contractor site and can take from 6 to 12 months to complete. The potential exists for mechanical and electrical failures during integration of the system into the SV.

Subsequent to SV integration and test are pre-launch, launch, and operations phases of the satellite system. The time required for these additional phases can vary significantly depending on the functionality and complexity of the satellite system.

Figure 2: GPS Satellite Box Assembly Process Flow Timeline



Satellite box assembly process = 113 to 160 weeks (approx. 2 to 3 years) total

SECTION 3: SUMMARY AND RECOMMENDATIONS FOR FUTURE WORK

Conformal coatings are used in space applications on printed wiring board (PWB) assemblies primarily as a protective barrier against environmental contaminants. Coating has been used at Sandia for decades in satellite applications including the GPS satellite program. There has been a perception that the conformal coating process and related processes are potentially troublesome, resulting in mechanical and electrical failures of coated electronic modules, resulting in damaged units requiring repair and production delays. There has also been disagreement on the necessary function of conformal coatings in electronic modules and whether coatings are needed at all. Until now, there has not been an examination of these potential conformal coating issues. This report is a result of an initial conformal coating value/risk assessment for Sandia satellite programs to attempt to address these concerns.

The primary benefit of conformal coating of electronics is protection from environmental contaminants including, dust, dirt, moisture, and corrosive vapors. During production and testing in the earth environment, and also in the zero-gravity space environment, there is the potential for random particles and contaminants to contact and span closely spaced electrical connections, possibly resulting in short circuits or other electrical failures that could cause partial or total loss of satellite functionality. Conformal coating is used to prevent these types of failures.

There are five primary types of conformal coating materials used for environmental protection of electronics: acrylics, silicones, polyurethanes, epoxies, and parylenes. Each type has a different combination of properties, with possible advantages and disadvantages in performance, processing, and removability.

There are also other possible benefits to using conformal coatings. Coating may provide a margin of structural integrity for components on electronic modules. They may also delay the formation of potentially damaging tin whiskers from pure tin on electrical component leads. While these benefits are potentially valuable, there had been limited work done in these areas, especially in documenting the structural benefits of conformal coatings for electronics.

There has been the perception that risks involved with conformal coating of electronics may outweigh the benefits. An initial examination of the conformal coating process and the failures that have been experienced indicated no serious problems that were inherent to conformal coatings or the coating process. As with all production steps involving the handling, assembly, testing, and transport of electrical assemblies, proper electrical grounding equipment should be employed for static sensitive components to prevent electrical failures, and proper handling and packaging should be used to avoid mechanical damage.

Conformal coating is a part of the entire assembly process for manufacturing satellite box assemblies. Satellite boxes are very complicated electromechanical assemblies that provide various functionalities to Sandia's satellite systems. Based on Sandia's previous experience with assembling satellite boxes, a GPS satellite box assembly timeline was constructed. It was determined that the entire box assembly process can take from 113 weeks to 160 weeks (approximately 2 to 3 years) to complete. The actual completion time for assembly of boxes in a system can depend on a number of variables including the availability of components and materials, complexity of the designs, and the type and number of assembly, handling, and testing problems (e.g., mechanical and electrical failures) that occur during the production process.

Based on what has been learned from this initial conformal coating value/risk assessment, the following items are recommended for future work in support of Sandia satellite programs:

- It is recommended that additional work be done to investigate the structurally beneficial effects of the various types of conformal coatings on satellite electronic modules as well the potential for failures to occur due to stresses induced on solder joints. Using a suitable electronic test structure, coated and uncoated specimens would be subjected to thermal cycling and shock/vibration environments. Failure analysis would be performed to identify any possible failures induced by the coatings. This work may also lead to a more reliable mechanical model of solder joint behavior in the presence of conformal coatings.

- The potential benefit of tin whisker mitigation provided by conformal coatings used in Sandia satellite programs should be studied. Understanding the ability of conformal coatings to delay the formation of tin whiskers may help to predict how long whisker formation could be delayed by conformal coating. Conformal coatings for tin whisker mitigation should be used in conjunction with proper electrical design and procurement of appropriate electrical components to avoid the occurrence of tin whiskers.

- It is recommended that further study be done to determine which of the available types of conformal coating may provide the best combination of properties and processing advantages for Sandia satellite programs including the ability to be removed so as to allow for repair of electronics after coating. A study comparing coatings based on properties, processing, and ease of removal could be conducted to arrive at the coating(s) having the best overall combination of these features.

- It has been questioned whether conformal coating is absolutely needed for space applications. Before a decision is made to stop using conformal coating, it is recommended that reliability testing of satellite electronics be done without conformal coating in environments replicating as much as possible the space environment including particle contamination.

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