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Conformal Coating Material and Application “State of the Industry” Assessment Report



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IPC-TR-587

Conformal Coating Material and Application “State of the Industry” Assessment Report

Developed by the J-STD-001 Conformal Coating Material & Application Industry Assessment (5-22arr) of the Assembly & Joining Committee (5-20) of IPC

Users of this publication are encouraged to participate in the development of future revisions.

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Conformal Coating Material and Application “State of the Industry” Assessment Report

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Abstract

Conformal coatings are thin layers of polymers applied to the surfaces of electronic assemblies, primarily to protect the electronics from the operational environment. In most manufacturing specifications, conformal coating thickness is defined as the thickness of the final polymer film on a flat, unencumbered surface of the assembly. However, the conformal coating thickness on other assembly and component surfaces are usually uncharacterized. This report outlines an IPC study of major conformal coating types, coating application techniques, and coating cure technologies, characterizing the final film thickness on common component surfaces. The study included volunteers from numerous manufacturing companies who applied coating using vetted manufacturing processes for the production of high reliability electronics.

Overview

Conformal coating, for the purpose of this document, is defined as a thin, often transparent, polymeric coating that is applied to the surfaces of printed circuit assemblies (PCAs) to provide protection from the operational use environment. Typical coating thickness ranges from 12.5 μm [0.49 mil] to 200 μm [7.9 mil].

Processing characteristics and curing mechanisms vary with the coating chemistries used. The desired performance characteristics of a conformal coating depend on the application and should be considered when selecting a coating material and process. Conformal coatings are used for the following:

- Inhibit current leakage and short circuit due to humidity and contamination from service environment
- Inhibit corrosion
- Improve fatigue life of solder joints to leadless packages
- Inhibit arcing, corona and St. Elmo's Fire in high voltage circuits
- Reduce damage from mechanical shock and vibration by providing mechanical support to small parts that cannot be secured by mechanical means.
- Provide some protection and mitigation against tin-whiskers and other conductive foreign objects or debris (FOD).

The beneficial effects of the coating depend on its properties, thickness and coverage. These characteristics in turn depend on the coating chemistry, application process and curing process.

The measurement of conformal coating thickness, in situ, has always been a tremendous challenge for the industry. Consequently, it has been an industry best manufacturing practice (BMP) is to measure conformal coating on a flat, unencumbered portion of the circuit assembly, or on a flat witness coupon processed at the same time as the circuit assembly. The J-STD-001 specification specifies thicknesses for conformal coating but those thickness ranges are for flat, unencumbered portions of the circuit assembly. It is a common misconception that the J-STD-001 specified thickness ranges apply to ALL surfaces of a circuit assembly.

The unanswered question is, when conformal coating is applied to flat, unencumbered surfaces of a printed circuit assembly such that it meets the thickness criteria of J-STD-001, what degree of conformal coating coverage can be expected on other critical surfaces, such as component leads, undersides of components, etc.?

In 2013, the J-STD-001 committee tasked a group of subject matter experts (SMEs) to answer this question by investigating conformal coating coverage in greater depth to determine the degree of conformal coating coverage that can be achieved by industry-standard conformal coating application/cure processes. Collins Aerospace led this massive effort, which involved a large number of volunteer sites.

Project Resources

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Executive Summary

A J-STD-001 task group was created to conduct the Conformal Coating Material & Application “State of the Industry” Assessment project. The objective of the project was to document the current “State of the Industry” of conformal coating application on printed wiring assemblies. The project was limited to the five major conformal coating types (acrylic, urethane, epoxy, silicone, Parylene (polyparaxylylene); i.e., AR, UR, ER, SR, XY) and standard methods of application (i.e., spray, dip, brush, vapor deposition). The project was specifically designed to not evaluate individual companies or specific conformal coating products; i.e., the project was to be a “blind” task activity. The output of the project was to produce baseline data on the thickness/coverage that industry conformal coating materials & process would achieve/expect on typical printed circuit assembly component technologies. The project results could then be used in industry studies/investigations relating to tin whisker mitigation, printed circuit assembly corrosion prevention, conformal coating process improvement, etc.

The project consisted of 26 data sets of test vehicles, each representing a coating type used, a method of application and a method of coating cure. Twelve volunteer facilities processed the 26 test vehicle data sets, reporting to the task group only those generic details necessary for understanding the conformal coating material and application method. All of the conformal coating processes used in this study were mature, qualified and being used on IPC Class 3 products to meet performance requirements in operational use environments.

The processed test vehicles were sent to Collins Aerospace for visual and metallographic analysis. The conformal coating on each test vehicle was inspected to the requirements of J-STD-001. All of the coated test vehicles conformed to the J-STD-001 specification. Photographic documentation was completed for each test vehicle using optical and black light capture methods. After visual inspection, the 26 data sets were prepared for cross-sectional analysis. Each data set consisted of three test vehicles that produced 78 metallographic cross-section samples for coating coverage/ thickness measurements. The conformal coating coverage/thickness measurements were then statistically analyzed.

The following are the take-way points for the project:

- The data in the study showed what levels and ranges of conformal coating thickness could be expected for various conformal coating materials, application methods, and cure methods.
- The conformal coating thickness on components resulting from these conformal coating processes were thinner than the observed thickness on the flat unencumbered surface, often less than the minimum specified flat unencumbered surface thickness in accordance with IPC-J-STD-001. IPC Class 3 hardware, which is regularly coated with these processes, produces acceptable field performance.
- All of the component surfaces examined in the study had some level of conformal coating present, even when that coating thickness was very thin.
- The data in the study should not be used to determine “acceptable/good” or “unacceptable/bad” coatings. Typically, the performance of an electronic assembly in a harsh environment (e.g., salt fog or corrosive gases) depends on the design of the enclosure, conductor spacing, circuit impedance, and conformal coating. A separate study would be needed to determine whether the observed thickness levels adequately protect electronic surfaces from specific external threat environments such as salt fog or corrosive gases.

Background

Environmental legislation (i.e., Restriction of Hazardous Substances (RoHS) European Union Directive) has significantly affected the electronic industry in terms of the materials used in electronic products. The prohibition of materials such as cadmium, hexavalent chromium, mercury and lead (Pb) has eliminated a number of electronic components and material processes that were historically used in producing electronic products. The removal of lead for solder alloys has arguably the greatest impact on electronic products due to its role as the primary mechanical and electrical functionality material. Figure 1 illustrates how global solder usage trends show the replacement of tin/lead solder alloys by lead-free solder alloys since 2004 as tracked by the IPC Global Solder Statistical Program [1].

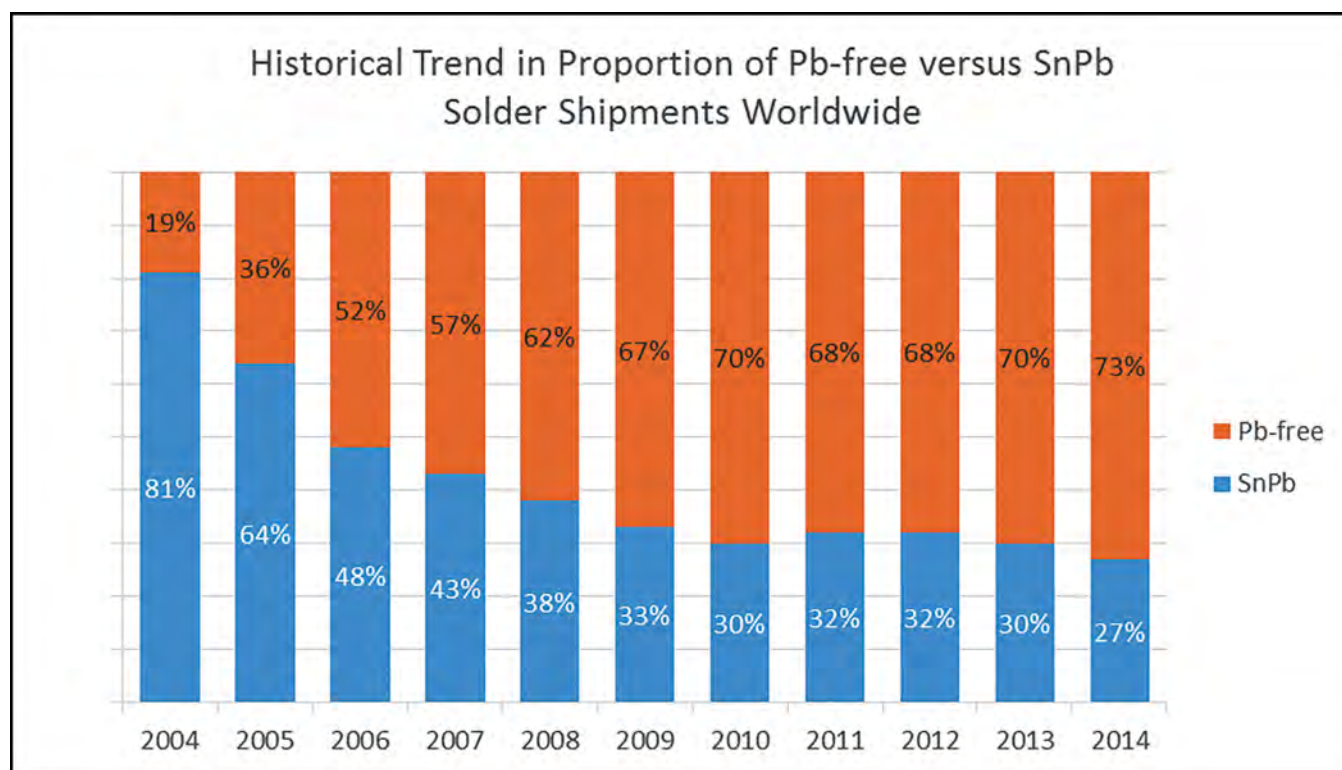


Figure 1 Global Solder Usage Trends [1]

The implementation of the RoHS Directive in 2006 led to pure tin becoming the dominant surface finish for component terminations. A drawback of pure tin surface finishes is the potential to form tin whiskers. The aerospace, defense and other high performance electronic industry segments have struggled to find a “comfort” zone of managing tin whisker risk due to both a lack of knowledge and industry consensus/acceptance on the validity of proposed mitigation methodologies. Using conformal coatings to contain/capture and prohibit penetration of tin whiskers is one commonly used mitigation approach. The industry acknowledges that there is no “perfect” conformal coating in terms of coating thickness and coverage, so the question is what constitutes “sufficient” for conformal coating application? Even a Parylene coating, which has industry consensus on having the most uniform, consistent thickness of the conformal coating materials, is not immune to tin whisker escapes/ruptures.

The topic of uniform conformal coating coverage/thickness for the purpose of tin whisker risk mitigation was first identified in 2009 by Dr. Michael Osterman, CALCE consortia, with the testing of 184 I/O Quad Flat Pack (QFP) component with pure tin plating [2]. Test vehicles containing the 184 I/O QFP components were processed with a variety of conformal coating materials including acrylic, silicone, urethane, and Parylene using traditional coating techniques/methods. The initial inspection of the test vehicles revealed sharp corners and component lead/termination edges to be the most susceptible to having thin conformal coating or minimal conformal coating coverage. Figure 2 illustrates typical QFP components on the test vehicles after coating. In these backscatter scanning electron micrographs, the coatings appear dark while bare or minimally coated portions of the terminations appear light.

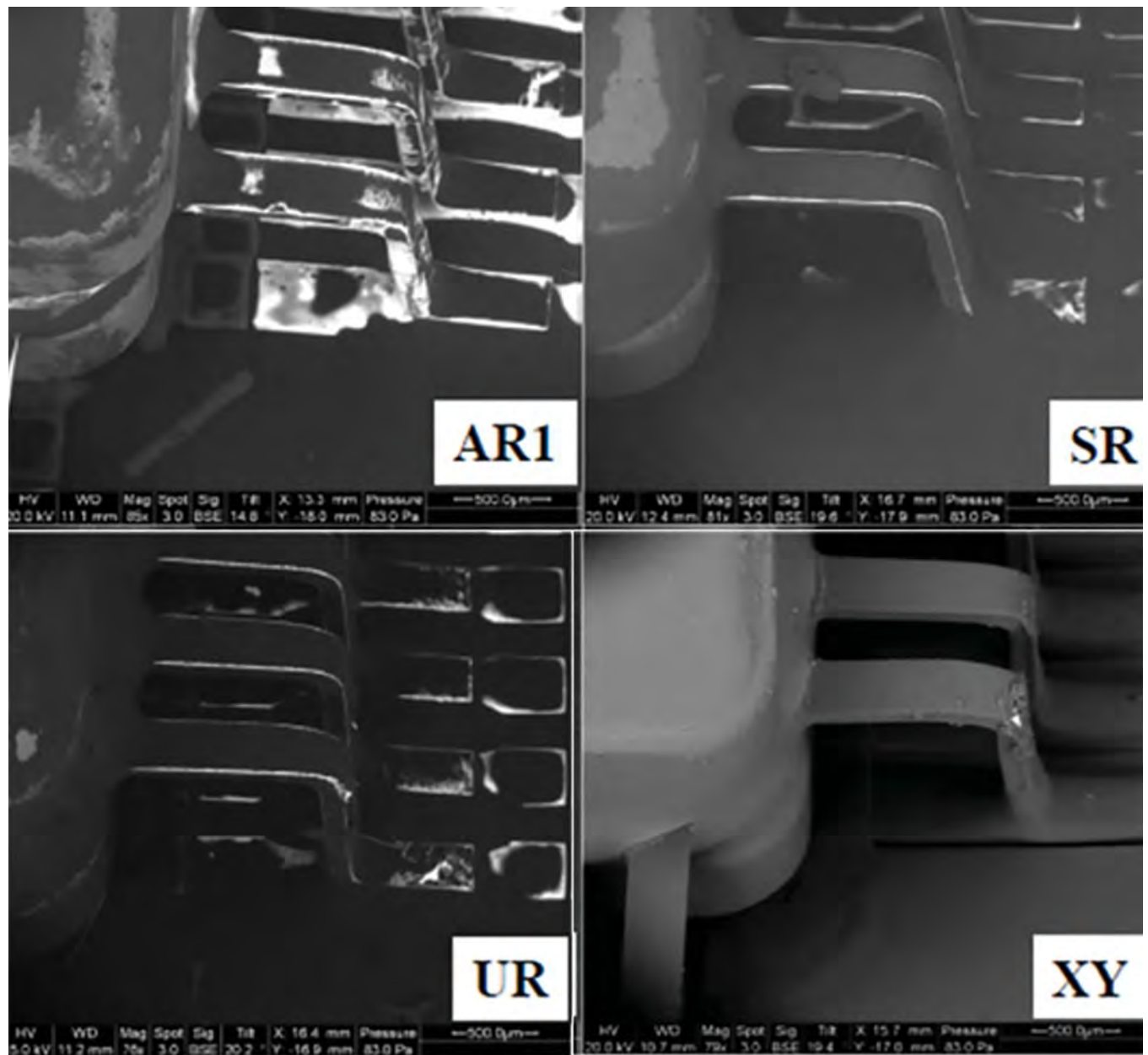


Figure 2 Osterman Study Initial Inspection of Conformal Coating Thickness/Coverage (Clockwise: Acrylic, Silicone, Paraxyllylene and Urethane)

After conditioning of the test vehicles was completed, a secondary inspection was conducted. It was clearly evident that that tin whisker growth was strongly associated with the minimally covered regions. Figure 3 illustrates tin whiskers not being captured/contained on the QFP component lead edges in the test vehicle.

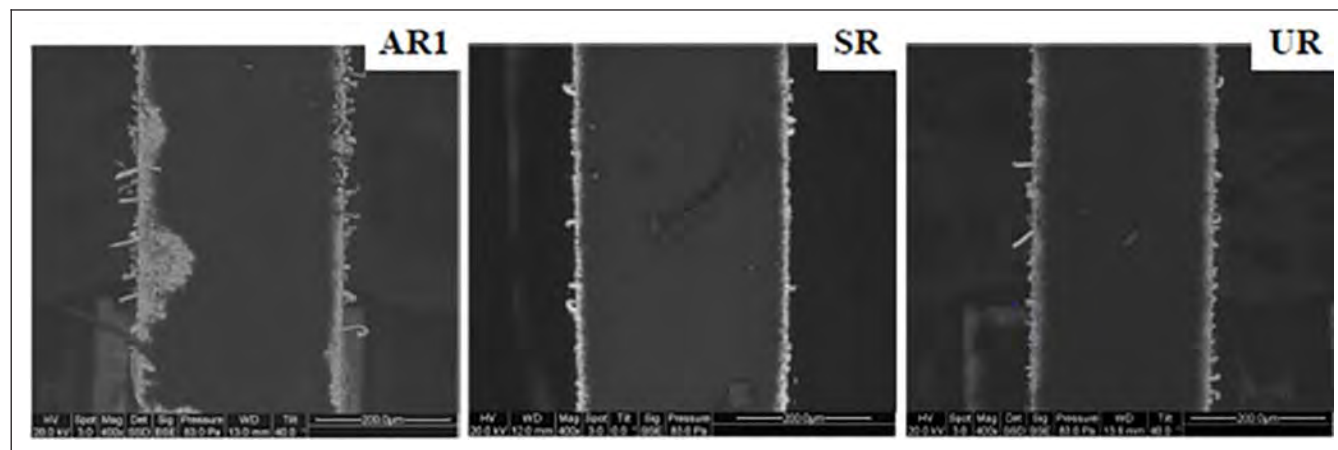


Figure 3 Osterman Test Coupons after Conditioning show evidence of thin whiskers (Left to Right: Acrylic, Silicone and Urethane)

The results from the Osterman testing were reported at an IPC Pb-free Electronics Risk Management (PERM) Council meeting in 2013. The PERM Council contacted the J-STD-001 committee, which initiated a conversation on how the topic of conformal coating coverage/thickness topic could be addressed in terms of a Workmanship Standards criteria approach. The ensuing discussions lead to an J-STD-001 task group conducting a Conformal Coating Material & Application “State of the Industry” Assessment project. The objective of the project was to document the current “State of the Industry” of conformal coating application on printed wiring assemblies. The project was limited to the five major conformal coating types (i.e., AR, UR, ER, SR, XY) and standard methods of application (i.e., spray, dip, brush and vapor deposition.). The project was designed to not evaluate individual companies or specific conformal coating products - i.e., the project was to be a “blind” task activity. The goal of the project was to produce baseline data on what thickness/coverage industry conformal coating materials & process would achieve on typical printed circuit assembly component technologies. The project results could then be used in industry studies/investigations relating to tin whisker mitigation, printed circuit assembly corrosion prevention, conformal coating process improvement, etc.

Design of Experiment (DOE) Parameters

Numerous test vehicles are used by the industry to examine/investigate material or process performance. The test vehicle selected for the project was the Practical Components PC009 printed circuit assembly (see Figure 4). The PC009 assembly contains a wide variety of plated-through-hole (PTH) and surface mount technology (SMT) component types that are representative of what is found on the majority of industry printed circuit assemblies.

The PC009 board did not contain a ball grid array (BGA) component. The task group decided that a BGA would not be included in the study because standard conformal coating process do not coat BGA solder balls due to adverse effects on solder joint integrity that can arise if the coating fills the package-to-board gap or forms a substantial fillet between the package and the board [3, 4].

The PC009 boards were assembled by Collins Aerospace using tin-lead solder paste and in-line saponified aqueous cleaning. A total of 100 PC009 boards were used in this assessment. A total of 26 data groups were developed.

There is a wide array of conformal coatings available in the industry. Historically, conformal coatings have been grouped by IPC-CC-830 into five coating families/types. In most cases, more than one specific formulation was used for a given coating family/type. The different formulations were anonymously tracked using letters (note, for example, that there is no relationship between Acrylic formulation A and Urethane formulation A).

- Acrylics – Type AR (formulations A, B, C, Z)
- Urethanes – Type UR (formulations A, B, C, D)
- Silicones – Type SR (formulation A, B, D, Z)
- Epoxies – Type ER (formulations A, B)
- Parylene (i.e., polyparaxylylene) – Type XY (formulation C)

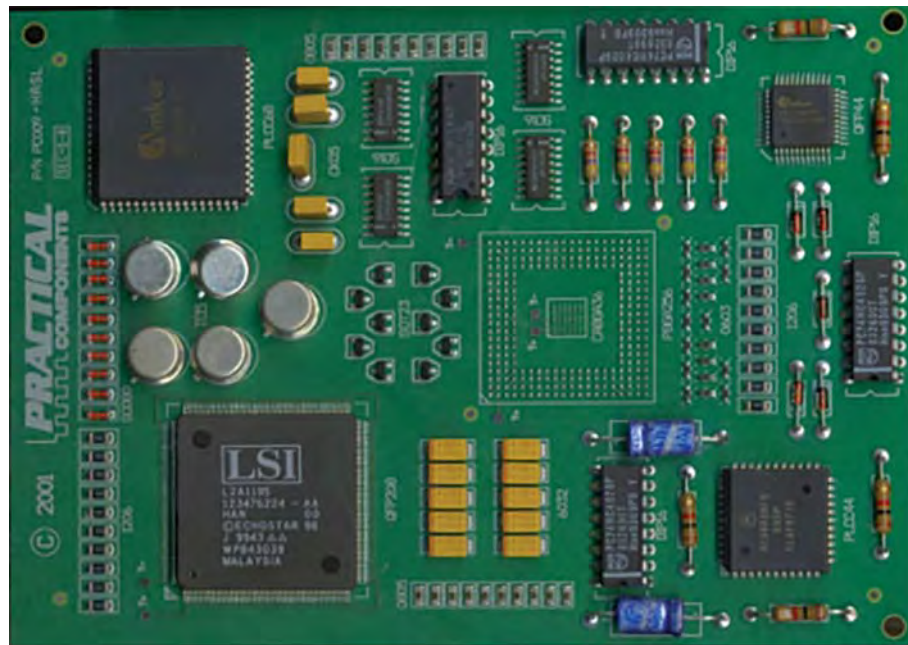


Figure 4 PC009 Test Vehicle

While other conformal coatings, such as fluoropolymers, are available, the SMEs chose to limit the study to the more conventional coatings typically used on high reliability hardware.

Table 1 shows the 26 sets of test specimens, showing the coating type used, a confidential material identification code, method of application and method of coating cure. The volunteers collected and retained specific material/process documentation, but the information reported to the task group only included the generic details necessary for understanding the conformal coating test vehicle character. After each of the volunteer sites had coated the test assemblies and cured the coating, the assemblies were placed into clean plastic bags and shipped to Collins Aerospace for analysis.

For each application, basic process information was provided by the volunteer facilities for potential differentiation within the application groups. The following are some examples of the process information submitted by the participants:

- **SR** – Manually Sprayed with Binks Model 2001 conventional gun at angle (approximately 45 degree) with applications at every 90 degrees (the boards are rotated to receive the angle spray from 4 sides to prevent shadowing).
- **UR** – Asymtek C740 equipment, SC300 atomizing head, 0.26 mm nozzle, 10 Degree flute, 10 psi fluid pressure, 30 psi atomizing pressure, 4 passes per path direction procedure.
- **ER** – Atomized Spray Coating, 10 passes each in X & Y axis, IR Profile followed by Batch Cure 45 min, 1 - 3 mils.

After the test vehicles were conformally coated, they were sent to Collins Aerospace for visual and metallographic analysis. The conformal coating on each test assembly was inspected to the requirements of J-STD-001 by a Collins Aerospace conformal coating subject material expert. All of the coated test vehicles were found to be in compliance with the J-STD-001 specification, i.e., the flat unencumbered thickness (FUT) surface criteria. Photographic documentation was completed for each test vehicle using optical and black light capture methods. Figure 5 illustrates the representative photographic documentation.

Table_1 Investigation Coating / Deposition / Cure Combinations

Set	Board Serial #	Material	Identification Code	Application	Cure
1	1, 2, 3	Urethane	A	Auto-spray, atomized	UV Cure
2	5, 6, 7	Urethane	B	Auto-spray, atomized	Heat Cure
3	8, 9, 10	Urethane	A	Auto-spray, atomized	UV Cure
4	11, 12, 13	Acrylic	C	Manual spray	Air/Heat Cure Combo
5	14, 15, 16	Silicone	A	Manual spray	Air Cure
6	17, 18, 19	Silicone	A	Manual spray	Air/Humidity Combo
7	20, 21, 22	Urethane	A	Auto-spray, atomized	UV Cure
8	23, 24, 25	Parylene	C	Vacuum deposition	Polymerized
9	26, 27, 28	Acrylic	A	Dip Coating	Air/Heat Cure Combo
10	29, 30, 31	Acrylic	A	Auto-spray, atomized	Heat Cure
11	32, 33, 34	Urethane	B	Auto-spray, atomized	Air/Heat Cure Combo
12	35, 36, 37	Epoxy	A	Auto-spray, atomized	Heat Cure
13	38, 39, 40	Acrylic	A	Manual syringe/Auto-spray, atomized	Air/Heat Cure Combo
14	41, 42, 43	Urethane	D	Auto-spray, atomized	Heat Cure
15	44, 45, 46	Urethane	C	Auto-spray	Heat Cure
16	47, 48, 49	Silicone	D	Auto-spray, atomized	Air Cure
17	50, 51, 52	Silicone	Z	Auto-spray, atomized	Heat Cure
18	53, 54, 55	Acrylic	Z	Auto-spray, atomized	Air/Heat Cure Combo
19	56, 57, 58	Urethane	A	Auto-spray, atomized	UV Cure
20	59, 60, 61	Urethane	B	Manual spray	Air/Heat Cure Combo
21	62, 63, 64	Urethane	A	Manual spray	UV Cure
22	65, 66, 67	Urethane	A	Auto-spray	UV Cure
23	68, 69, 70	Silicone	A	Manual spray	Heat Cure
24	71, 72, 73	Silicone	B	Auto-spray	Heat Cure
25	74, 75, 76	Epoxy	B	Auto-spray, atomized	Heat Cure
26	94, 95, 96	Acrylic	B	Manual Brush	Heat Cure

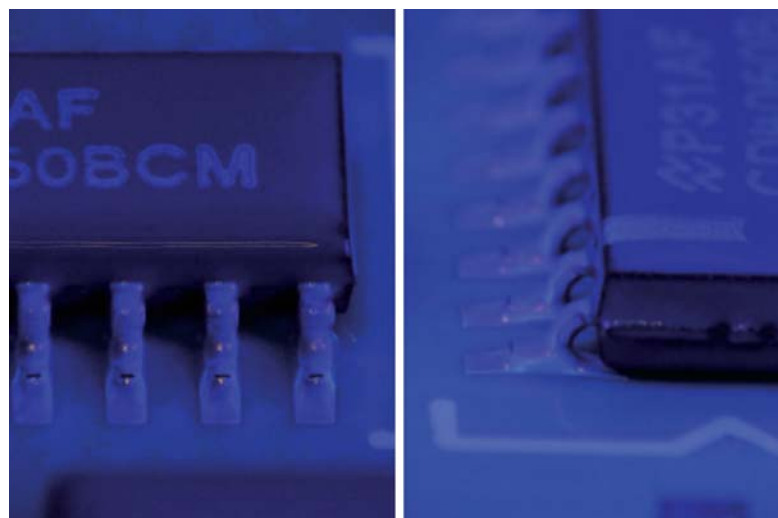


Figure 5 Representative Photographic Documentation of Conformally Coated Components Using Black Light Showing Minimal Coating Coverage

Cross-Sectioning Procedure

After visual inspection, the test vehicles were prepared for cross-sectional analysis. Each data set consisted of coverage/thickness measurements from 78 metallographic cross-section samples from a total of three test vehicles.

The following metallographic cross-sectional analysis procedure was used:

1. Designated components were removed from each test vehicle and controlled so as to ensure that the chain of evidence was intact. Any remaining sectioning debris was carefully cleaned off such that the conformal coating was not altered.
2. Using a SEM gold sputtering system, a thin layer of gold was deposited over each designated component. The thin layer of gold provided a visual boundary between the candidate coating and subsequent layers of overcoating or potting material.
3. Each specimen was overcoated with Cytec CE-1155 urethane material using an air cure to create an outer smear cap coat layer. This overcoat of a rigid two-part urethane coating prevented tear-out of softer coatings during the grinding and polishing operations used in cross-sectioning.
4. Metallographic cold mounts were prepared using a 24 hour cure epoxy option and vacuum de-airing procedure. Validation of individual mount labeling and linkage to the file folder data was completed to ensure sample identification was not compromised.
5. Metallographic cross-sectional grinding and polishing using a series of diamond compounds was completed. Vibromet final polishing was completed immediately prior to photo-documentation.
6. Photo-documentation emphasized capturing conformal coating thickness and uniformity data. Conformal coating thickness was measured for each designated component per the file folder test plan using the metallographic microscope measurement system.

Metallographic cross-sectional analysis was conducted for both the end view and profile view of the component leads with an emphasis on component leads where a tin whisker short risk was present (Figure 6).



Figure 6 Metallographic Cross-Section Angles: Profile (left), End (right)

Analysis Procedure

All of the test results were entered into a Microsoft Excel spreadsheet that was periodically provided to the IPC committee for review. The final edition of the spreadsheet, titled “IPC Conformal Coat Plotter Rev AD.xlsx,” is available from the IPC. Appendix A describes how to utilize the spreadsheet for comparison assessment. The spreadsheet incorporates filters to allow examination of the various test parameters and measured coating thicknesses.

The following components were included in the assessment:

- | | |
|--------------------|--------------------------|
| • Axial Diode | • SMC6032 |
| • Axial Resistor | • SMR0603 |
| • CK05 | • SMR0805 |
| • DIP16 | • SMR1206 |
| • Electrolytic Cap | • SO16 |
| • PLCC44 | • SOD80 |
| • PLCC68 | • SOT23 |
| • QFP208 | • TO5 |
| • QFP44 | • Flat unencumbered area |

The yellow dots in Figure 7 show the 25 component sample locations on each test vehicle (the flat unencumbered area is not marked). A total of 78 cross-sections were completed for the three vehicles in each data set.



Figure 7 PC009 Board with Components Selected for Metallographic Analysis

Appendix B of this document shows each of the 26 locations that were examined in this study, documenting typical minimum, maximum, and top of component measurements locations for each electronic component. Note that the indicated locations are not all-inclusive of the areas that were measured for the project. Minimum, maximum, and average thickness measurements could vary depending on coating material and application method.

- Two typical minimum and maximum measurements were taken on leaded parts (QFP44, QFP208, PLCC68, etc.). When a leaded component was cross-sectioned across multiple leads, multiple measurements were taken and the back side of leaded components were also examined for coverage.
- Conformal coating was present on the backside of leads but was generally too thin for an accurate measurement; when this happened, a notation was made in the Master Conformal Coating Measurements Spreadsheet.
- The minimum and maximum readings were for leads only, i.e., they did not include the measurements for the tops of components or flat unencumbered surfaces. Minimum and maximum measurements were on conductive surfaces only.
- Appendix B documents the typical component measurement locations. Figure 8 illustrates a typical Appendix B component graphic of the typical coating measurement areas.

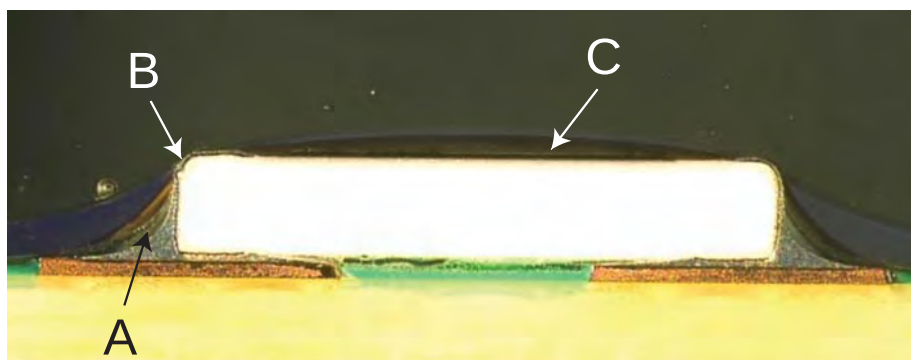


Figure 8 Representative Appendix B Graphic Showing SMR1206 Documenting Typical Measurement Areas

- A: Typical Maximum Measurement
 B: Typical Minimum Measurement
 C: Typical Top of Component Measurement (Trace amount)

Coating Application Methods

The purpose of this project was to establish an industry baseline of current conformal coating application methods and to review what these coating methods produced among 26 different application subsets. These 26 sets covered the five standard material types: AR - Acrylic Resin, UR - Urethane Resin, ER - Epoxy Resin, SR - Silicone Resin and XY - Parylene and included six different cure methods: Heat Cure, UV Cure, Air Cure, an Air/Heat Combo, Polymerized and an Air/Humidity Combo.

In generating these various subsets, the identity of each volunteer was kept confidential. Fundamental information was obtained from each volunteer so that the 26 subsets could be categorized into five standard manufacturing processes, with a sixth manufacturing process consisting of a process that was specifically modified to enhance lead coverage.

These conformal coating manufacturing processes were: manual spray, automated spray, vapor deposited, dip deposited, manual brush, and manual syringe & automated spray combo as explained further in the following paragraphs.

Table 2 Test Board Numbers for Application/Material Combinations Included in the Investigation

Application / Type	AR	UR	ER	SR	XY
Manual Spray	11, 12, 13	59, 60, 61 62, 63, 64		14, 15, 16 17, 18, 19 68, 69, 70	
Automated Spray	29, 30, 31 53, 54, 55	1, 2, 3 5, 6, 7 8, 9, 10 20, 21, 22 32, 33, 34	41, 42, 43 44, 45, 46 56, 57, 58 65, 66, 67	35, 36, 37 74, 75, 76	47, 48, 49 50, 51, 52 71, 72, 73
Vapor Deposited					23, 24, 25
Dip Deposited	26, 27, 28				
Manual Brush	94, 95, 96				
Manual Syringe / Automated Spray	38, 39, 40				

Manual Spray

Manual spraying is commonly used when low volumes of parts need to be coated, when the assembly topography is too varied for automated coating, or when automated coating processes are unavailable. In manual operations, aerosol cans or handheld spray guns, such as high-volume low pressure (HVLP) guns or conversion spray guns, can be utilized. Manual spraying is very operator dependent: operator skill can strongly influence the quality, coverage, consistency and uniformity of the coating on the PCA. A black-light inspection is typically employed to verify coverage. Hand touch-up, using a brush or syringe, may be required.

Aerosol Spraying Aerosols have a low solids content (less than 5%), so ventilation of the spray area is paramount. Spray is applied in a horizontal position to prevent the flow of coating into undesirable areas and to produce a more consistent film build. Masking is highly recommended. To ensure total coverage, a thin coating (approximately 0.025 mm [1 mil]) is applied during each pass and the board is rotated 90° after each pass. While initial startup costs for an aerosol application system may be low, efficiency is a concern. Material utilization for aerosol applications is typically 25% to 40% because a significant amount of coating material can be wasted due to over-spray and coating applied to masked areas.

Handheld Gun Spraying Handheld spray gun operations are generally very similar to aerosol applications. Proper ventilation should be ensured. Again, the spray application should be completed in a horizontal position in a series of 4 passes of thin (0.025 mm [1 mil]) coating, with the board being rotated 90° after each pass. Masking is again highly recommended. A hand-held spray operation should utilize a spray gun, a material reservoir and a cycle actuation device (trigger assembly, valve controller, etc.). Many spray gun manufacturers supply handheld spray guns that can be effectively used for manual operations (Figure 9). Fluid and air pressure can be regulated to produce a fine, atomized spray. When a material reservoir is used, it is important that the conformal coating raw material is pressurized with dry, un-lubricated air or nitrogen. This is especially prudent for moisture cure coatings, which may take on cured characteristics if exposed to unfiltered air for a prolonged period of time.

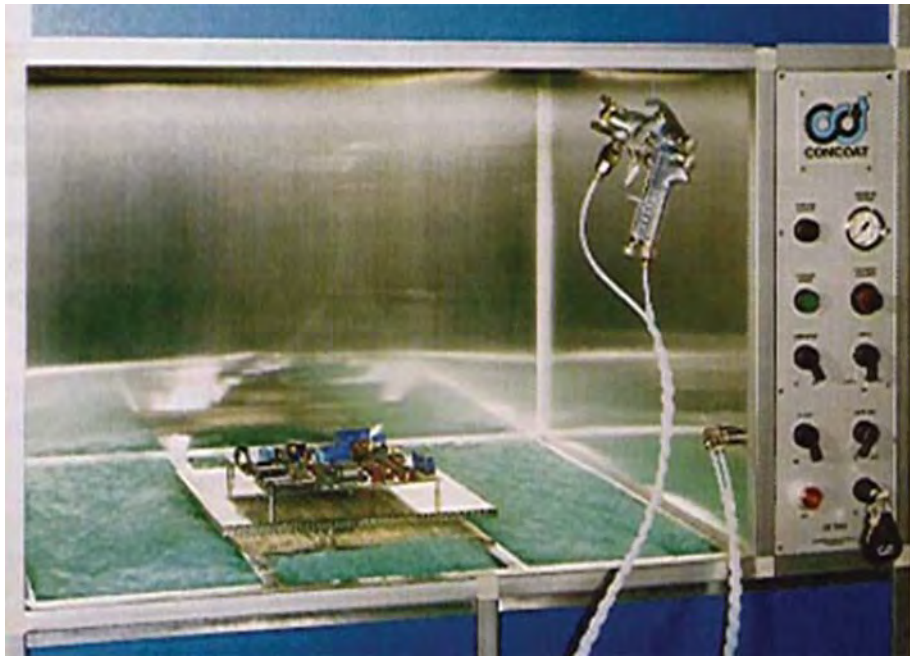


Figure 9 Hand Held Spray Gun Configuration

Particular care should also be taken when spraying UV-curable coatings. Due to the presence of UV in sun and light sources, clear feed lines should not be used between the reservoir and the spray head. Black or opaque tubing can easily eliminate any concerns over UV light altering the coating process.

Handheld spray operations can be a quick and relatively inexpensive avenue into a conformal coating process. Since spray heads can accept higher viscosity fluids than aerosols dilution may not be required. A more controlled spray process can improve transfer efficiency, however, this is dependent on the time and complexity of the PCA.

For handheld spraying, an open-faced spray booth is required to contain overspray and odors. Per NFPA - “National Fire Protection Standards” specifications, an airflow of 30.48 m/min [100 ft/min] should be present over the entire booth opening. This can translate into exhausting a considerable amount of conditioned air (Volume of conditioned air, in ft³/minute = 30.48 m/min [100 ft/min] multiplied by the booth opening size in ft²). If the booth is used to rack the wet parts and let them air dry, the booth especially needs to be larger and the exhaust be turned on for extended time periods. Conditioning (temperature, humidity) make-up air can be expensive, so it should be included when evaluating the operating costs. In aerosol or manual spray operations, and where solvent-based coatings are being employed (except water-based coatings), the operator should be provided with adequate respiratory equipment. The spray booth has filters to trap solids and allow the vapor to pass through. These filters need to periodically be replaced and they may be considered a hazardous waste, depending on the local regulations and the particular coating materials that are sprayed.

Automated Spray

Automated spraying is effective for spraying high volumes of similar or mixed parts. Two different methods can be used to automate a spray process: a reciprocating spray system or a selective coating unit.

Automated systems offer a few advantages over manual spray operations. See Figure 10 for examples of automated atomized and non-atomized application methods. Automated systems increase throughput capabilities and provide a more uniform coating. With automated equipment, the machine controls the quality and does not require a specially trained operator. Some training is necessary for operators and maintenance, but these individuals should not require special skills beyond those of other production personnel.

Automated equipment also requires ventilation in the spray chamber, as specified by the manufacturer. Some automated spray equipment includes an oven, which is located directly after the spray chamber that ensures that the parts leave the system a tack-free state. This eliminates the need to handle parts while they are still wet. Depending on the coating, ovens should be constructed to safely handle any flammable vapors that could be generated during the curing process.

A reciprocating sprayer includes a belt conveyor that transports a masked PCA into the spray area. A bank of spray heads moves back and forth over the PCAs to produce an even film. Material tanks feed each spray head similar to what is used in the manual process.

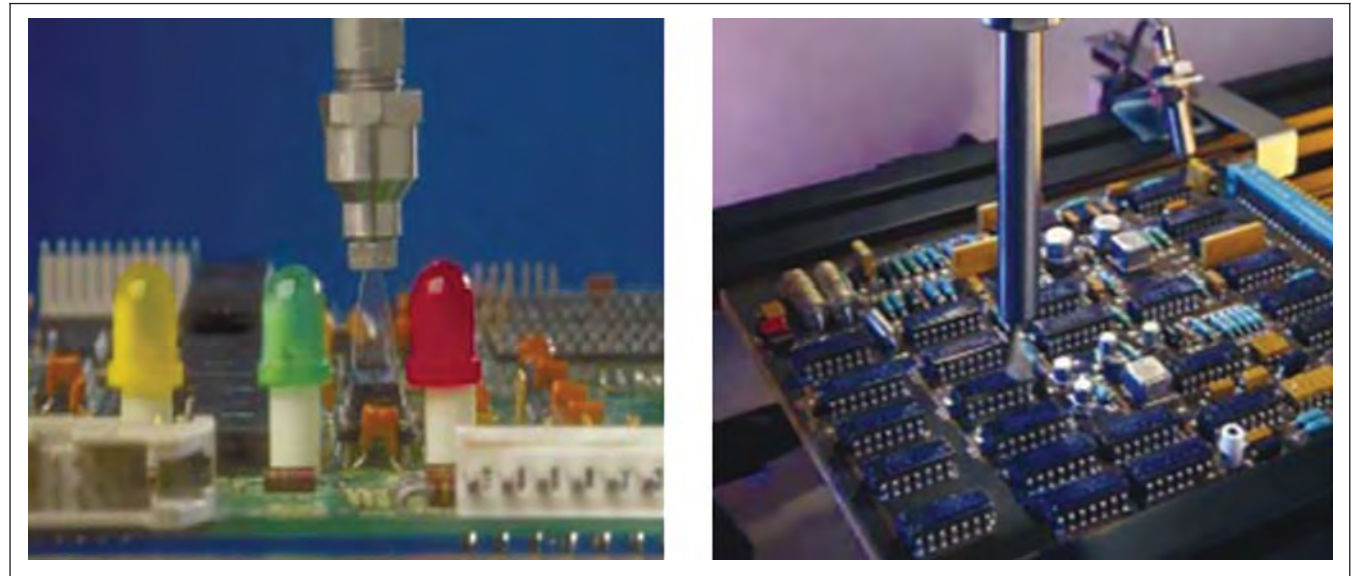


Figure 10 Automated Spray Configurations: Non-atomized Curtain Coater (left), Swirl Applicator (right)

Although material will still be lost due to overspray and coating applied to masked areas, through proper system design it is possible to achieve a coating transfer efficiency (TE) in the 80% range. The material utilization can be maximized by optimizing the placement of PCAs on the conveyor. Variables such as temperature, valve, air cap and nozzle design, atomization pressure, humidity and flow rate all affect the overall efficiency of the automated spraying system. Generally, the viscosity of fluids that are sprayed is lower than those used for dipping.

Vapor Deposited

Parylene (XY) films and certain other ultra-thin coatings are deposited on a substrate in a vacuum chamber by vapor deposition polymerization (VDP) (see Figure 11). As a gaseous process, the coating penetrates minute spaces and covers all exposed surfaces. It is used when total coverage and protection are required. Non-coated areas can be masked using various methods.

Films can be accurately deposited, in thicknesses ranging from submicron to several mils, with high uniformity, repeatability and predictability. Parylenes have very high dielectric properties, are excellent moisture and corrosion barriers, are low out-gassing, and, as a pure polymer, have very good long-term stability. Vapor deposited materials with other polymer chemistries can provide unique coating properties such as hydrophobic surfaces or excellent corrosion resistance.

This coating process requires special vacuum equipment and specially trained operators or the use of a coating service provider. Due to its uniformity and repeatability, only one subset of Parylene was included in the study to establish a process baseline comparable to other standard manufacturing conformal coating application processes.



Figure 11 Parylene Conformal Coating System

Dip Deposition

Dipping is a low cost, efficient way to apply a conformal coating. In this method, a PCA is immersed into a bath of coating liquid (see Figure 12). Masking of sensitive areas is required and assemblies should be oriented vertically, rather than horizontally, when dipped. Coating thickness is established by the immersion and withdrawal speeds. Typical recommended immersion speeds are 152 mm to 305 mm/min [6 in to 12 in/min]. Once immersed, the PCA should remain in the bath until all bubbling has ceased. The PCA is then withdrawn at least slowly enough that any air surrounding the components is displaced, so that no air remains trapped in the final coating.

The withdrawal rate from the dipping process should be slower than the cascade effect of the coating. This can typically be 25 mm to 152 mm/min [1 in to 6 in/min]. The slower the withdrawal rate, the thinner the coating on the assembly. Faster withdrawal rates and lower viscosity materials may cause coating to flow and can produce an uneven coating over the PCA. This is simply a product of gravity and should be evaluated prior to implementation. Material manufacturers can recommend proven ways to prevent solvent loss and material cure within the dipping process.

Dip coating is a common choice in high volume production, since jigs or carriers may be employed to allow as many as 40 PCAs to be coated simultaneously. This commonly equates to around 500 PCAs per hour. To achieve this high production rate, care must be taken to minimize or eliminate the need for masking. That can be accomplished, for example, with PCA designs that locate all components that should not be coated onto one edge of the assembly that is not immersed into the coating liquid.

Only one subset of dip coating was included as a process baseline to other standard manufacturing conformal coating application processes, due to its recognized consistency and uniformity.

Manual Brush

Brushing may be used to coat a limited quantity or specific areas of PCAs. This is a labor-intensive operation that is not generally suitable for high production rates. This application method consists of using a brush or similar device to manually “paint” the coating onto a PCA. This can reduce the need for masking, due to the highly controlled nature of the process. Brushing is most often used in a repair or touch-up work. It is difficult to achieve uniform film characteristics (thickness, etc.) over an entire PCA with this method.

Care must be taken to prevent air bubbles from forming during the application process. The operator’s goal should be to flow, rather than paint, the coating on to reduce the introduction of air. It may be necessary to restrict the process to only one or two strokes of the brush to reduce the possibility of air introduction.

Additional consideration should be given to moisture-cure coatings, which may change viscosity when exposed to ambient air during application. An appropriate solvent or cleaning agent can be used to remove cured coating from the brush.

Since manual brush application leads to much higher variability than the automated coating processes, only one subset of this method was included to establish a baseline that could be compared to other standard manufacturing conformal coating application processes.

Manual Syringe and Automated Spray Combination

A potentially enhanced conformal coating coverage layer could be produced by combining two different application technologies: manual syringe and automated spray. In the initial manual syringe process, conformal coating was manually applied to the leads of high-profile components such as QFP-25, QFP-50 J-Lead, and PTH. The purpose of this step is



Figure 12 Dip Conformal Coating System

encapsulate the leads with the excessive conformal coating material. This is a labor-intensive operation that may not be suitable for high production rates and which also does not typically lead to uniform film builds over an entire component. The manual syringe process should utilize similar approaches for preventing the formation of air bubbles, as described for the manual brush method. Similarly, the additional care for preventing ambient air from affecting brushed moisture-cured coatings also apply to syringe-applied.

The syringe process would be followed by a multi-layer atomized spray application. When multiple layers are required, vendors should be consulted to recommend appropriate multi-layering techniques. Certain chemistries require complete cure before subsequent coating while others may require partial cure. It is not a common practice to utilize surface treatments, to improve adhesion, between coating layers; however they have been used in some unique cases.

The user should keep the recommended coating thickness requirements in mind. With some materials, multi-layering o may substantially increase the total film build because additional material may be needed to wet the surface of the previously applied layer.

It was hypothesized that this hybrid process could lead to an improved coating since the multiple layers would dull the otherwise sharp edges at the component leads and thereby lead to thicker local coverage than could be achieved with a standard, single-coating application. One subset of this combined approach was included in the study to establish a process baseline that could be compared to the conventional manufacturing conformal coating application processes.

Coating Cure Methods

As noted within the application section, the purpose of this project was to establish an industry baseline of the current conformal coating application standards and to review the resulting coating coverage and thickness among 26 various application subsets. These 26 subsets covered the five standard material types; AR – Acrylic Resin, UR – Urethane Resin, ER – Epoxy Resin, SR – Silicone Resin and XY – Parylene.

Each volunteer organization provided basic process information to categorize the 26 sets into four standard manufacturing cure methods, as well as two modified cure method combinations to mitigate bubbles and provide a uniform conformal coating finish. The six manufacturing conformal coating cure processes utilized were: Heat Cure, UV Cure, Air Cure, Polymerized, Air/Heat Combo, and Air/Humidity Combo. The test board numbers in which these different cure methods, which are described in the following paragraphs, are listed in Table 3.

Table 3 Test Board Numbers for Cure Method/Material Combinations Included in the Investigation

Cure / Type	AR	UR	ER	SR	XY
Heat Cure	29, 30, 31 94, 95, 96	5, 6, 7 41, 42, 43 44, 45, 46	35, 36, 37 74, 75, 76	50, 51, 52 68, 69, 70 71, 72, 73	
UV Cure		1, 2, 3 8, 9, 10 20, 21, 22	56, 57, 58 62, 63, 64 65, 66, 67		
Air Cure				14, 15, 16 47, 48, 49	
Air/Heat Combo	11, 12, 13 26, 27, 28 38, 39, 40 53, 54, 55	32, 33, 34 59, 60, 61			
Polymerized					23, 24, 25
Air/Humidity Combo				17, 18, 19	

Cure Mechanism

Cure is defined as the completion of chemical cross-linking and/or solvent evaporation to develop full coating properties. Cure mechanisms are different for liquid and vapor deposited coatings. Coating material types and their associated cures are discussed extensively in IPC-HDBK-830. The cure mechanisms used in this test program were depended on the specific conformal coating chemistry. Some materials employ a dual cure to ensure complete curing of all the coating material applied to a PCA along with process combinations that minimize bubble formation. The majority of the coatings evaluated were liquid cross-linking coatings that contained some solvent. However, some were non-solvent, UV-cure, cross-linked coatings while others were non-cross-linking acrylic thermoplastics. Liquid thermosets are either two components mixed together or a single component. One-component, liquid thermoset coatings are typically cross-linked by exposure to heat or

temperature, humidity, oxygen, or ultraviolet light. Two-component liquid thermosets, which usually begin curing immediately after the two parts are mixed together at room temperature, are often thermally accelerated. Thermoplastic coatings, on the other hand, are solvent thinned and require solvent evaporation to harden.

Cure Process Considerations

Cure processes may take several hours to several days, depending on the conformal coating chemistry. Material suppliers should be consulted to determine cure schedules. If final testing or “burn in” are done after the coating operation, the time required for the selected material to reach optimum properties needs to be considered.

Characteristics of “cured” conformal coatings are provided in the material supplier’s technical data sheet. If the recommended curing conditions of the supplier are not strictly followed, end results will likely vary.

Air Cure (a.k.a. Room Temperature Cure)

Air curing is the lowest cost and longest cycle time process of the various cure methods. This process is commonly used when low volumes of parts need to be coated and/or high viscosity coating materials are used to mitigate bubble/void entrapment during the curing process. In this cure method, the coating is cured in an ambient environment; depending on the material classification, exhaust may be used to remove by-products that are released during this process. If the coating is solvent based, it should be subjected to room temperature cure to evaporate the solvent, to prevent solvent from being entrapped, prior to any subsequent cure. Some coatings may be accelerated by the application of mild heat or humidity; this will be discussed further within these other cure processes. The room temperature cure method is most commonly done either in an open area that is covered or in an oven or chamber with no heat added.

Heat Cure

Heat curing has been one of the most common cure methods for several years, as some materials require elevated temperatures to initiate their curing. In general, these coatings cure more quickly than room temperature and moisture cure coatings. The coating is cured with the application of a specific thermal profile that is provided by the material supplier based on the coating material and thickness.

Some room temperature curing may be accelerated by the application of heat, however, the acceleration of a moisture cure coating may also require additional humidity as well as elevated temperature. Coating material suppliers should be consulted to determine the specific conditions for accelerated curing. The heat cure method is most commonly done either in a batch oven or in an in-line convection or IR oven operating with a material-specific thermal profile.

UV Cure (a.k.a. Ultra-violet Cure)

UV curing has the shortest cycle time process of the various cure methods. Currently, this is a process that is seeing increasing use due to recent development of new coating formulations. Most UV curable conformal coatings now contain a secondary cure mechanism to cure any coating material that flows under devices and therefore cannot absorb the UV energy. The secondary mechanisms for the photo-initiator modified coatings can be ambient moisture for silicones (SR), and catalyzed, heat, aerobic, or ambient moisture for the organic AR, ER, and UR materials. Aerobic UV chemistries are not totally effective, depending on the fillet formation thickness and the ability of ambient air to diffuse through and penetrate the coating fillet. The wavelength, intensity and duration of the UV source should be verified with the appropriate material supplier.

This type of cure method most commonly uses either a handheld UV tool or an oven or chamber with a UV energy source. Care should be used in selecting the UV cure methods, as different UV energy sources and accessories should be validated as acceptable per the coating supplier’s recommendations.

Polymerized Cure (a.k.a. Vapor-phase Polymerization)

Polymerized curing, which may need to be done over a period of hours, has one of the longest process time cycles of potential coating cure methods, many of which only require seconds and minutes. This process commonly is used for most vapor deposited coatings that are polymerized, or “cured,” during the deposition process. Since this type of cure method is most commonly done within the application equipment, neither post-application treatment nor additional equipment for curing are required.

Air/Heat Combo Cure

Air/Heat combo cure combines the low cost long cycle time process of air curing that is included in various cure process with the most common cure method used to accelerate the process (heating) to reduce the standard curing time. Use of this process is growing since it can reduce the formation of bubbles and voids while reducing the overall cure cycle time.

little as a few minutes, rather than the hours that may be required for conventional air curing. In this process, an initial air cure is followed by a secondary cure in an elevated thermal environment. Depending on the material classification, exhaust may be required to remove byproducts that are released during this process. Care is required to ensure that the elevated thermal cure does not begin too early and is not at a high enough temperature that bubbles are trapped within the coating layer. This cure method is most commonly done either in an open area that is covered with a batch or in-line oven or in an air buffer prior to a convection or IR oven with a thermal profile.

Air/Humidity Combination Cure (a.k.a. Air/Moisture Combination Cure)

Moisture Cure

Before this curing combination is discussed, some background information on moisture “humidity” cure processes is needed. Moisture cure materials react with ambient moisture - so the ambient relative humidity at the time of exposure directly impacts the speed of cure initiation. Humidity cure methods are low cost (slightly higher than an air only cure process), but a long cycle time is required.

When using humidity cure, caution should be exercised to prevent ambient humidity from initiating premature curing either during storage or the application of coating, or in any processes subsequent to the initial coating application that rely on the coating being in an uncured state. For coating applications that utilize humidity in the curing process, thicknesses larger than a few mils will require a longer cure time.

As with room temperature cure coatings, moisture cure coatings can also be accelerated by mild increases of temperature and humidity. The elevated temperature is typically no more than 65 °C [149 °F]; the material supplier should be consulted to determine the specific conditions that should be used.

This type of cure method typically uses either a batch oven “and water” or an in-line convection or IR oven with a thermal profile and humidity profile built within the equipment set.

Air/Humidity Combination Cure

The Air/Humidity combination cure consists of an initial air cure followed by exposure to a controlled, elevated humidity. Use of this process is growing, both because it can help reduce bubble/void entrapment during the curing process, but also to better ensure that the final film is fully cured, provided that the overall cure cycle time to a few or more hours.

This cure method is typically done either in an open-air area that is complemented with an in-line oven with humidity options or in an air buffer prior to a convection or IR oven with a thermal profile and humidity option.

Test Results

The purpose of this project was to establish an industry baseline of current industry methods used to understand the variations resulting from different materials, applications and cure methods used for conformal coatings.

Overall, the 26 various application sets that were produced covered the five standard material types; AR – Acrylic Resin, UR – Urethane Resin, ER – Epoxy Resin, SR – Silicone Resin and XY – Poly-Parylene. To compare and contrast data by application method, these 26 sets can be grouped into the six application types.

- Manual Spray – 3 subsets (AR, UR and SR)
- Automated Spray – 4 subsets (AR, UR, ER and SR)
- Vapor Deposited – 1 subset (XY)
- Dip Deposited – 1 subset (AR)
- Manual Brush – 1 subset (AR)
- Syringe & Spray – 1 subset (AR)

Table 4 Investigation Application Method/Material Subset Distribution

Application / Type	AR	UR	ER	SR	XY
Manual Spray	11, 12, 13	59, 60, 61 62, 63, 64		14, 15, 16 17, 18, 19 68, 69, 70	
Automated Spray	29, 30, 31 53, 54, 55	1, 2, 3 41, 42, 43 5, 6, 7 44, 45, 46 8, 9, 10 56, 57, 58 20, 21, 22 65, 66, 67 32, 33, 34	35, 36, 37 74, 75, 76	47, 48, 49 50, 51, 52 71, 72, 73	
Vapor Deposited					23, 24, 25
Dip Deposited	26, 27, 28				
Manual Brush	94, 95, 96				
Manual Syringe / Automated Spray	38, 39, 40				

The material applications also consisted of six different cure methods; Heat Cure, UV Cure, Air Cure, an Air/Heat Combo, Polymerized and an Air/Humidity Combo that can be grouped into 10 cure type subsets:

- Heat Cure – 4 subsets (AR, UR, ER and SR)
- UV Cure – 1 subset (UR)
- Air Cure – 1 subset (SR)
- Air/Heat Combo – 2 subsets (AR and UR)
- Polymerized – 1 subset (XY)
- Air/Humidity Combo – 1 subset (SR)

Table 5 Cure Method/Material Subset Distribution

Cure / Type	AR	UR	ER	SR	XY
Heat Cure	29, 30, 31 94, 95, 96	5, 6, 7 41, 42, 43 44, 45, 46	35, 36, 37 74, 75, 76	50, 51, 52 68, 69, 70 71, 72, 73	
UV Cure		1, 2, 3 56, 57, 58 8, 9, 10 62, 63, 64 20, 21, 22 65, 66, 67			
Air Cure				14, 15, 16 47, 48, 49	
Air/Heat Combo	11, 12, 13 26, 27, 28 38, 39, 40 53, 54, 55	32, 33, 34 59, 60, 61			
Polymerized					23, 24, 25
Air/Humidity Combo				17, 18, 19	

Overall, the conformal coating coverage was not always visually uniform, and was often thin. Regardless of the material chemical family, application process, or component type, coating thickness was never zero. (Figure 13).

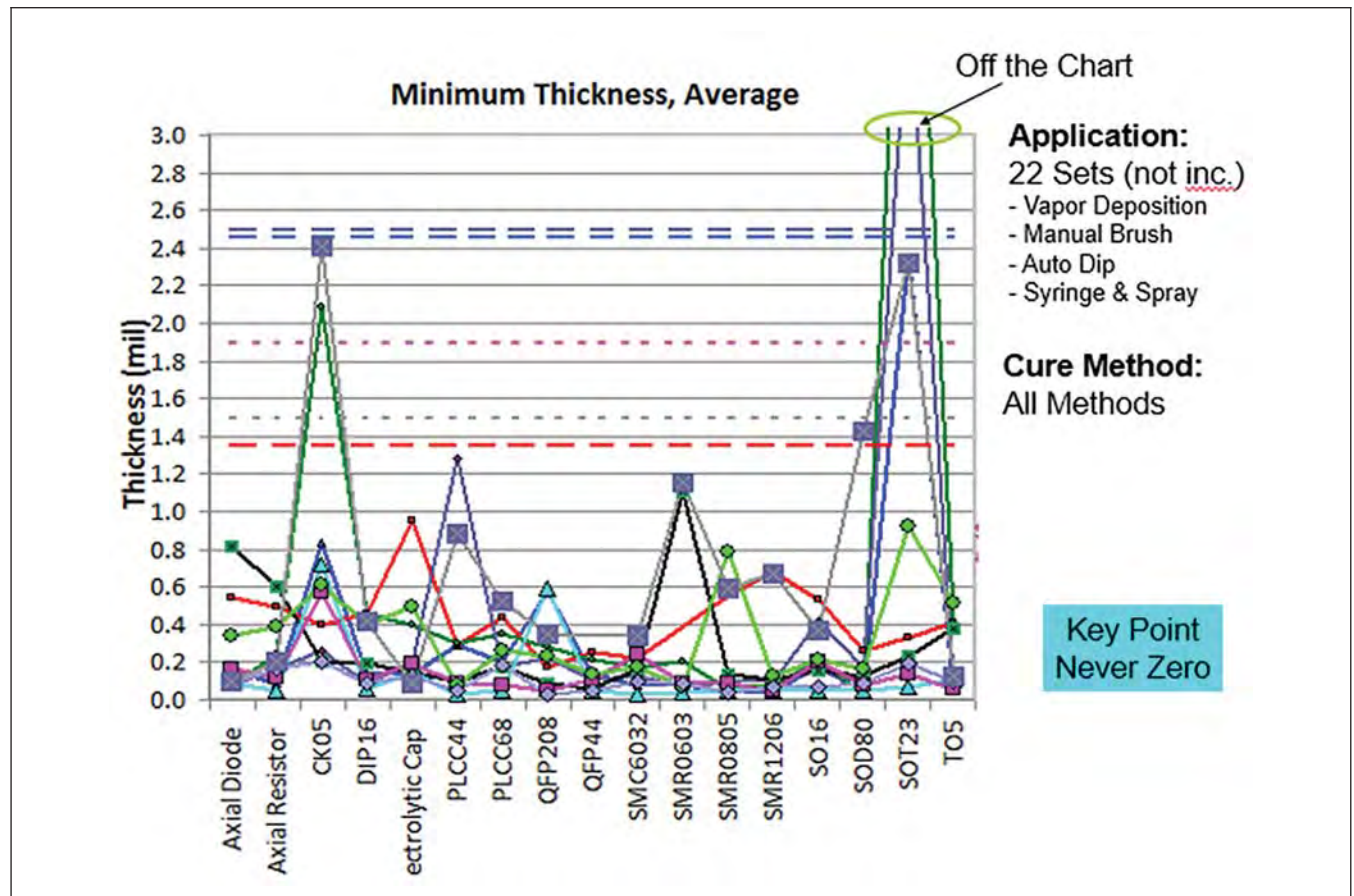


Figure 13 Conformal Coating Minimum Thickness Results Show that in all Cases the Coating Thickness was Non-Zero

Material Comparison by Chemical Family

The following sections compare conformal coating materials, by chemical family, for the 26 test data sets using the average minimum coating thickness metric for each component type. Figures 14 - 48 are used to compare different data sets; the data sets are described in the legend or as labels that use the following format: material, material recipe designator, application method, cure method, volunteer designator. For example, the description “Acrylic, Z, Auto-spray atomized, Air/Heat Cure Combo, H” corresponds to the data set for the Z formulation of acrylic coating that was applied with an atomized spray using automated equipment, cured with a combination Air/Heat combination cure process and done by Volunteer H.

AR – Acrylic Resin Coating Materials

Acrylic coating materials have most commonly been seen as the first line of environmental protection for harsh environmental conditions. This is due to their ease of application and reworkability due to their sensitivity to solvent based materials. As these materials are the most commonly used materials, they were applied with the widest variety of methods including: Manual Spray, Automated Spray, Dip, Manual Brush and the Syringe/Auto-Spray Combo processes.

The following observations were visible amongst the data collected (Figure 14, Figure 15)

1. Manual Brush & Dip Process, showed similar nominal thickness, while the Manual Brush Process had higher peaks of coverage along with greater variability. Both of these subsets (shown in green and red lines on Figure 14) had higher nominal thickness and process variability as compared to the Manual and Auto Spray processes.
2. The coatings that were sprayed (black, blue and light blue) had the lowest variation from their nominal thickness values.
3. The Syringe/Auto-Spray combo (purple line) as compared to the results for other sprayed coatings (black, blue and light blue lines) did have a higher nominal thickness and the majority higher peaks of coverage.
4. Overall, this data shows the spray coating can achieve much better consistency than with brush application.

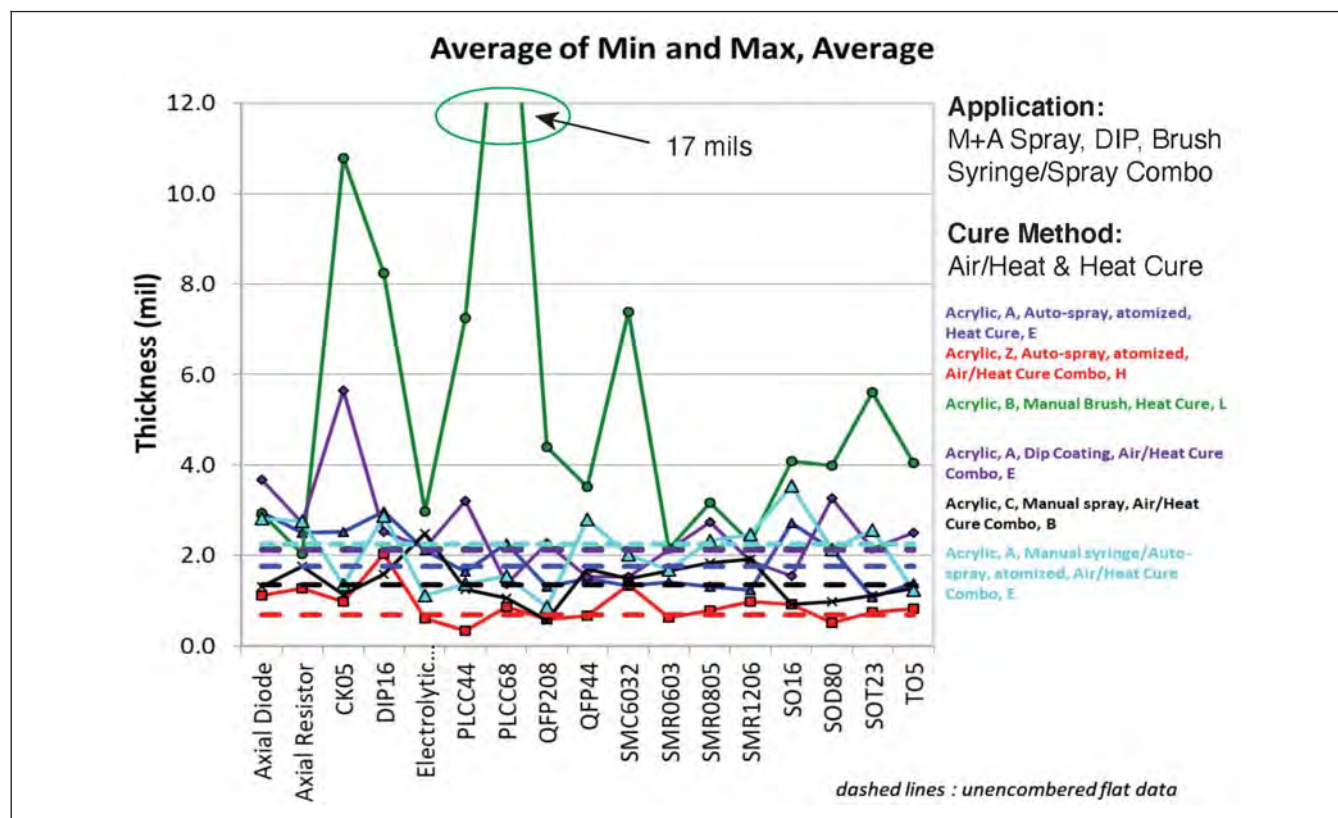


Figure 14 Average of Min and Max AR Materials (mils)

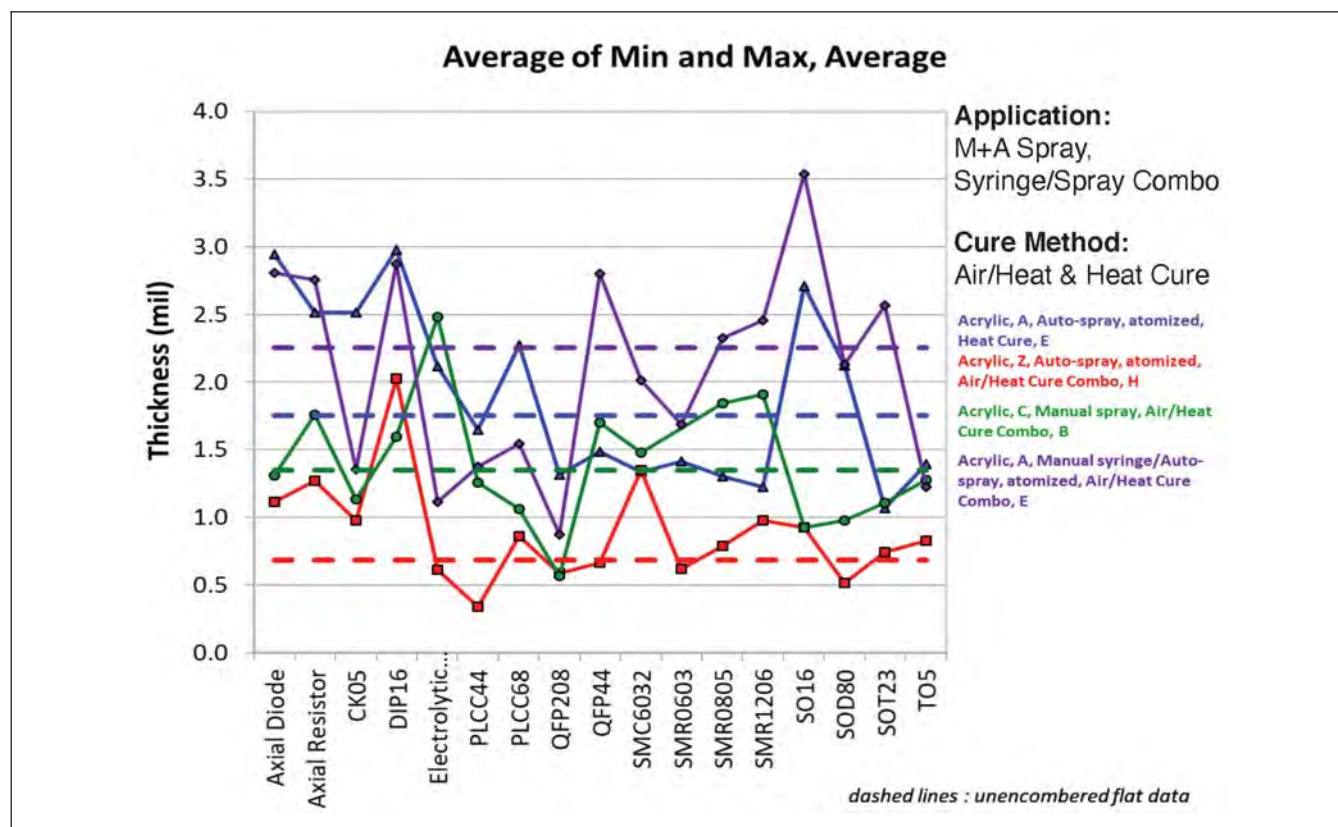


Figure 15 Average of Min and Max AR Spray Applications (mils)

UR – Urethane Resin Coating Materials

Urethane coating materials are the second most popular coating protection in harsh environmental conditions. Their resistance to solvent-based materials makes them more difficult to rework than acrylic materials - but it also makes them more robust in environments that may expose them to solvents. In this investigation, these materials were applied with both Manual Spray and Automated Spray processes.

Figure 16 shows results for all of the automated spray UR coatings included in this investigation. The graph is extremely crowded; it is shown here to provide an overview of the variations that are within this subset group. Subsequent graphs that show subsets of these data will provide better insight into factors that influence UR coating characteristics.

The following observations on how the automated spray processes affect UR coatings can be made from the results shown in Figure 16.

1. The nominal thicknesses for the automated spray processes with UR coating centered around 1.75 mils $\pm$ 0.25 mils, with the Heat Cure Methods leading to higher nominal thickness as compared to either the UV or Air/Heat Cure combo cures.
2. The nominal thickness resulting from Air/Heat Cure Combo was in a similar range as the UV Cure group. However, this combination cure (shown in the black line) thickness, was consistently lower than the other heat cured coatings shown in red, light blue and magenta).

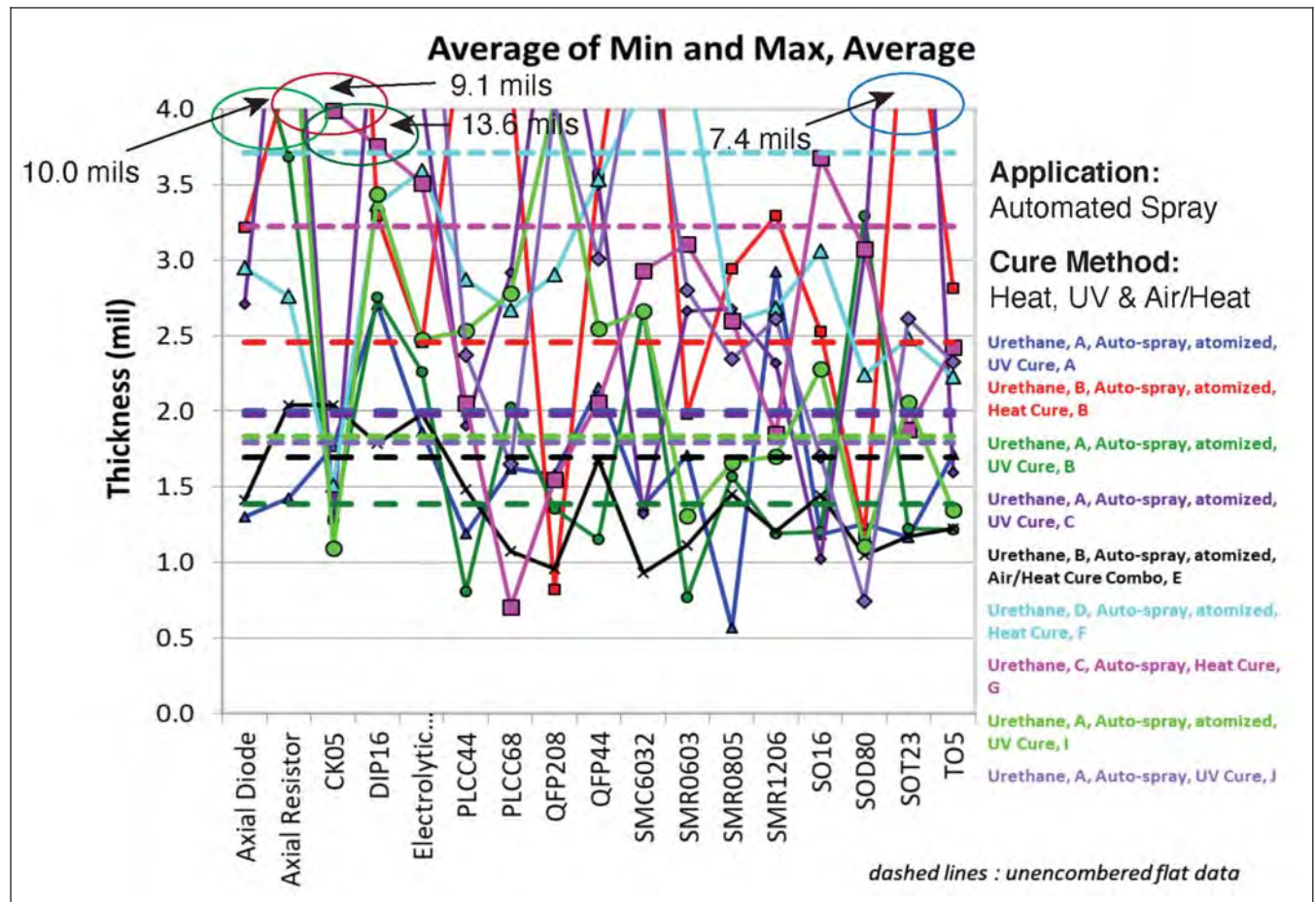


Figure 16 Average of Min and Max UR Materials (mils)

Figure 17 – 20 show a subset of the results depicted in Figure 16 so that specific combinations of application and cure methods for UR coatings can be compared. Figure 17 shows three results for Auto-sprayed application combined with Heat Cure, as conducted by three different volunteers.

1. The nominal coating thickness for the three sets were in the range of 2.5-3.7 mil; local coating thicknesses on different parts and for different coatings ranged from ~0.7 to 5.6 mil, with one component exhibiting a thickness of over 9 mil in one case.
2. The coverage from Volunteer B (blue line) had more variability than those from Volunteers G and F. Also, the component-level variations for coatings from Volunteers G and F were more consistent, i.e., the peaks and valleys in the plots generally track each other for those two data sets.
3. While the subset coated by Volunteer F (red line) had the largest FUT of the three subsets shown, its component coating thickness was generally not the largest (i.e., a larger FUT does not necessarily correspond to consistently thick coating on components.)

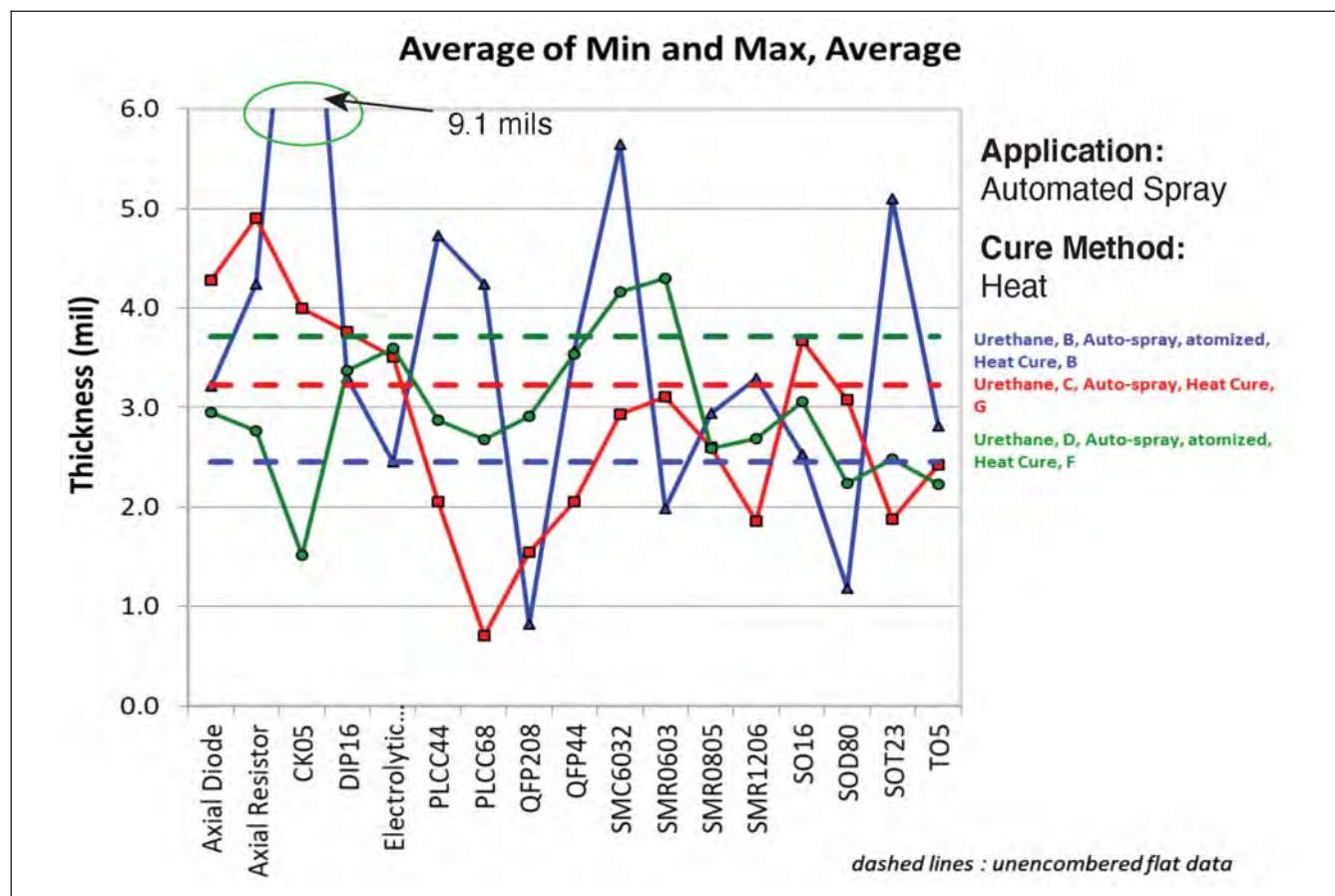


Figure 17 Average of Min and Max UR Auto Spray/Cure Applications (mils)

Figure 18 compares the Auto and Manual Spray and Air/Heat and Heat Cure Methods for the 'B' formulation of Urethane coating.

1. The FUT of the three coatings ranged from 1.7 to 4.7 mils while the local thicknesses ranged from ~1 to 5.5 mil, with one data point at 9.1 mil.
2. The manual spray coating (green line) had much higher FUT than the two auto-sprayed coatings (red and blue), but the variability between parts was similar to the auto-spray/heat cure combination (red line)
3. The minimum thicknesses for all three combinations was ~1 mil on the same parts (QFP208 and SMC6032).
4. The subset noted in the red line had a lower nominal thickness than the green, but the coverage was higher at points.

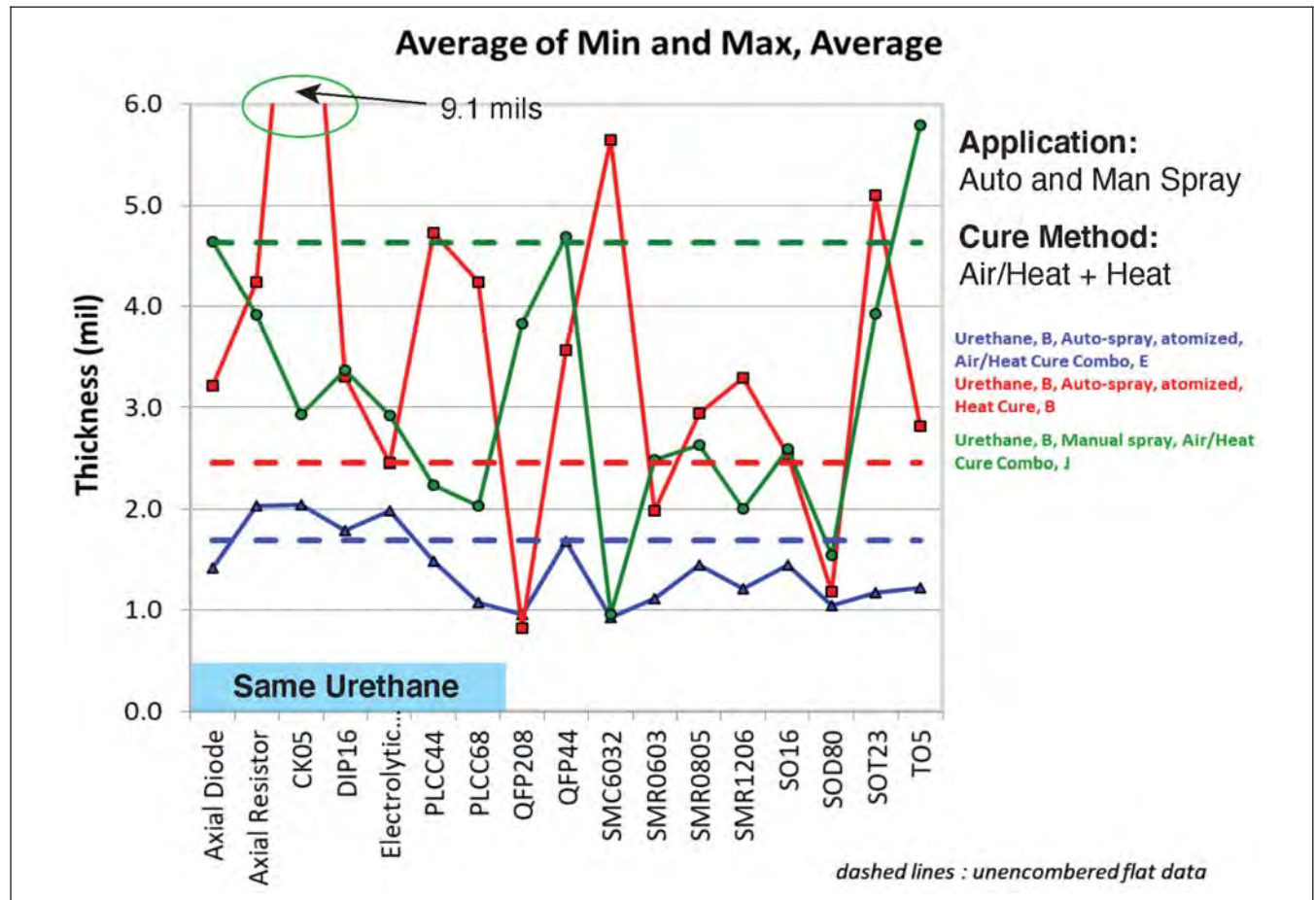


Figure 18 Average Min and Max UR Spray/Air+Heat Cure Applications (mils)

Figure 19 compares results for a single type of UV cured Urethane coating (type A) that was applied with either auto or manual spray processes.

1. At ~4.8 mil, the FUT for the manual spray case (red line) is significantly larger than the thickness for auto sprayed coatings (1.5-2 mil). However, the coating thickness on individual parts is generally similar for the two application methods.
2. Other than a few exceptions, the majority of the component coating thicknesses were between 1 and 6 mil; some outliers with greater thickness were observed as were a few local regions with thickness as low as ~0.5 mil.
3. The subset noted in the black line had a lower nominal thickness than the others, but the coverage was either higher or the same for the various component technologies evaluated.

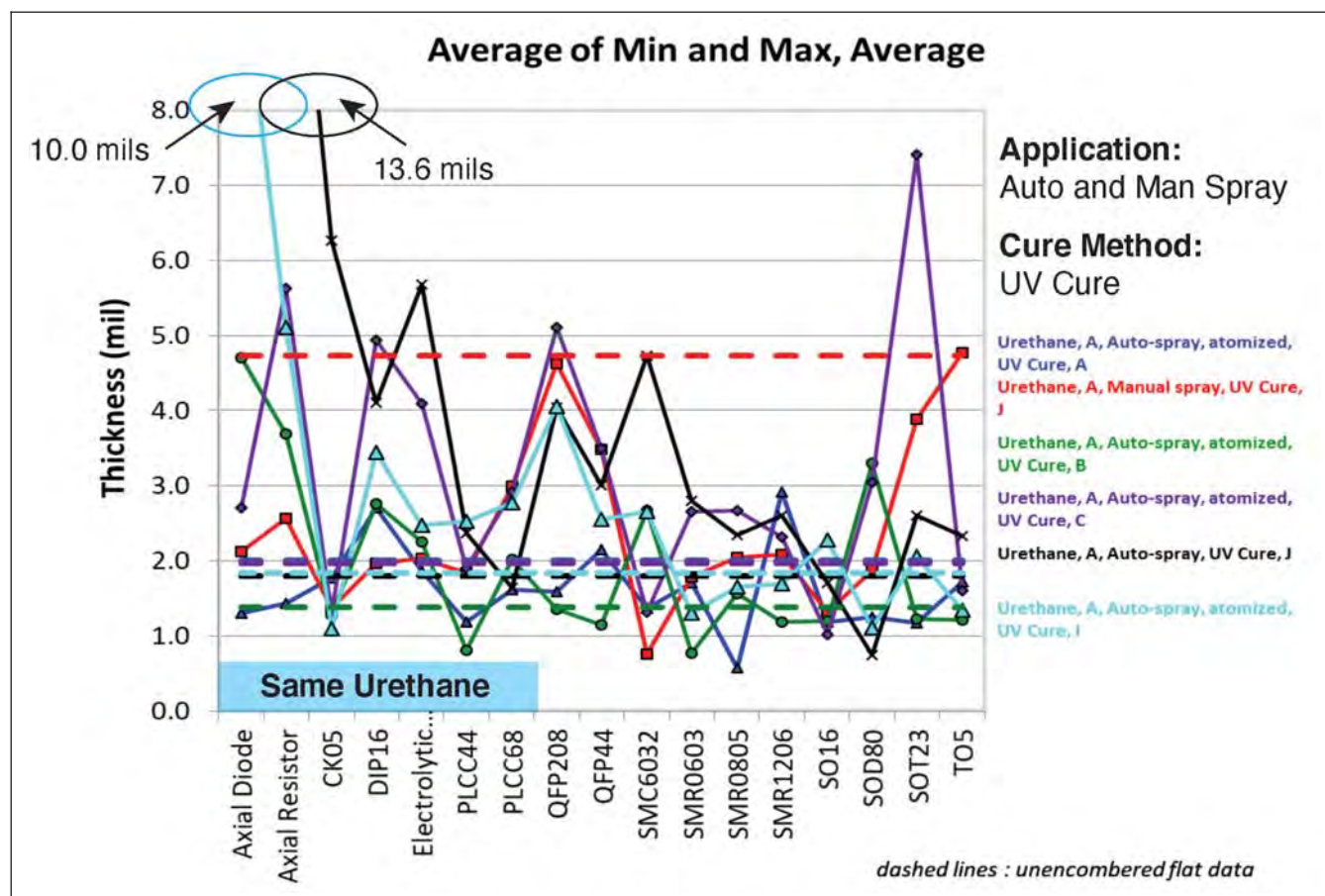


Figure 19 Average of Min and Max UR Spray/UV Cure Applications (mils)