CONFORMAL COATING 101: GENERAL OVERVIEW, PROCESS DEVELOPMENT, AND CONTROL METHODS

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ABSTRACT
Have you ever wondered what conformal coating is all about? What are the PROs and CONs of conformal coating? What materials are involved? Which materials work best? How to inspect the coverage and thickness? Can all PCB surfaces be coated? What does it take to keep the process stable and repeatable? This presentation/paper will go through the general information on the process, materials, process setup, and control methods we used to answer all these questions and more.

Keywords: Conformal Coating, Surface Energy, Silicone, Acrylic, Urethane, Potting, Process Qualification, Masking

INTRODUCTION
What is Conformal Coating?
Wikipedia definition: Conformal coating material is applied to electronic circuitry to act as protection against moisture, dust, chemicals, and temperature extremes that, if uncoated (non-protected), could result in damage or failure of the electronics to function. When electronics must withstand harsh environments and added protection is necessary, most circuit board assembly houses coat them with a layer of transparent conformal coating rather than potting.

As stated in previous definition, it’s a coating that protects assemblies against:

- Humidity
- Corrosive materials
- Contamination (particulate or otherwise)
- Mechanical stresses

It also increases electrical clearance tolerance.

CONFORMAL COATING VERSUS POTTING
Potting does the same thing as conformal coating except that it seals the electronic circuitry from all environments inside a shell or mold. But...

- Reworking is not as easy or even impossible given the material used.
- Conformal Coating could yield the same harsh environment protection with the advantage of rework-ability.

COATING PROCESS DEVELOPMENT CYCLE
Conformal coating is not as easy as you may think. There are a lot of factors that go into determining the reliability of the coating for the circuit boards intend use. It is not just slapping down a layer of paint.

Below is an outline of the development steps and questions the coating process needs answered to be reliable:

1. Determine what you are trying to protect the assembly from and which materials support this need.
2. Determine the surface energy of the assembly to ensure that the assembly can be coated (with the chosen material).
3. Develop the Requirements (with the Vendors)
   a. Required thickness
   b. Keep out areas
   c. Materials
   d. Acceptance criteria
4. Develop the Process
   a. Spray Patterns, Dip or Manual Steps
   b. Tooling (Pallets, Special Nozzles, Brushes, etc.)
   c. Machine Programs
   d. Cure Process & Times
   e. Viscosity
   f. Test Coupons
   g. Temperature & Humidity Controls
5. Clean the assembly?
6. How to mask non-coating areas?
7. How to apply coating?
8. How to cure coating?
9. Unmask board before or after curing?
10. What about repair/touchup?
11. Inspection method?
12. Process control methods?

Answering each of these questions will lead to the most stable process and reliable coating.

CONFORMAL COAT TYPES
Your first step is to determine what environment your product will be exposed to and for how long. This will determine the material type almost immediately. Figure 1 shows the different coating materials and application methods used predominantly for them. In order to keep costs low, application method must be in mind during the selection process. Be aware that the application method may require a capital investment affecting the total cost of your coating needs.
From BTW, Inc.’s experience, we broke down the material advantages and disadvantages on five material types based on eight considerations that could affect material selection (see figure 2). These five materials are Acrylic, Silicone, Urethane, PTFE, and Parylene.

**Acrylic** conformal coatings are the most popular of all conformal coating materials due to their ease of application and reworkability. Acrylics dry rapidly, reaching optimum physical properties within an hour; have a good temperature range; are a good insulator; are durable; and provide long pot life under inert atmosphere. Additionally, acrylics give off little or no exothermic heat during cure, eliminating potential damage to heat-sensitive components. They do not shrink during cure and have good humidity resistance and exhibit low glass transition temperatures. Acrylic coatings can be easily removed for rework using solvents. However, this does not allow them to be used in any chemical environment. Spot removal of the coating to repair a solder joint or replace a component can be easily accomplished by localized solvent application. Although not encouraged, Acrylic coatings can be soldered through if needed. [1]

**Silicone** conformal coating is a flexible overlay that provides a protective coating for printed circuit boards against high temperatures, moisture, corrosion, and thermal shock. It protects and insulates electrical and electronic components and assemblies, including generators, motors, transformers, relays, and solenoid coils [2]. Silicone conformal coatings are second in popularity. One big disadvantage of silicone is when atomized, it can migrate everywhere in a facility therefore having an affect all other materials and processes (i.e. solder de-wetting). However, the fundamental problem with this property is that since nothing sticks to the surface, it is hard to get parylene to adhere to the substrate; in reality, parylene does not bond well to the substrate or surface it is applied to. In an application where any force is applied perpendicular to the weak surface bond, as in the case of sliding friction, the parylene coating has a tendency to dislodge from the substrate. Also, parylene has a very low coefficient of thermal expansion. When applied to a substrate with a moderate degree of thermal expansion (i.e., stainless steel), thermal cycling can create shear stress in the already weak bonds between the parylene and the steel surface causing failure of the coating system. Parylene application sometimes requires temperatures high enough to introduce metallurgic stresses in metal substrates and cause weaknesses and physical distortions or deviation from metric specifications. Finally, parylene has a fairly low thermal limitation endpoint in that it sublimates and decomposes to the vapor monomer at low temperature [5]. Special equipment is required to produce a xylene environment for vapor deposition.

**Urethane** conformal coatings are perfect for extreme chemical conditions. It is a durable finish product that provides a protective coating for printed circuit boards against moisture, corrosion, and thermal shock [3]. Urethane is low in cost and has multiple methods for application. Its only drawbacks are that it is very difficult to repair urethane coated circuit boards and has a short pot life.

**PTFE** (PolyTetraFluoroEthylene) (also known as Teflon) is a fluorocarbon-based conformal coating. PTFE coatings can provide a low co-efficient of friction or slipperiness, corrosion and chemical resistance, heat resistance, dielectric stability, and chemical inertness to the circuit assembly. In addition, PTFE coatings are bio-compatible [4].

While PTFE is inert, adhesion is problematic to certain surfaces. It is difficult to make thin conformal coatings and impossible, in fact, on the inner diameters of small deep recesses. PTFE is very soft and easily damaged through normal handling [5]. Special equipment is required to produce a fluorinated environment for vapor deposition.

**Parylene** conformal coating is a thermoplastic which can be deposited on various substrates to form a nearly uniform, continuous layer. It is generally inert and has a low coefficient of friction. However, there are several key limitations inherent to parylene, which may make it unsuitable for applications that are subject to friction, pressure, heat or thermal cycling.

Parylene is very soft. It has a low durometer value and has the approximate hardness of human skin. A very soft coating is easy to damage during routine handling, and any scratch to the surface of the substrate defeats the coating system entirely. Parylene is inert and has very few active sites to form intra-molecular bonds with other chemicals—this is why parylene is considered a “nonstick” surface of sorts. However, the fundamental problem with this property is that since nothing sticks to the surface, it is hard to get parylene to adhere to the substrate; in reality, parylene does not bond well to the substrate or surface it is applied to. In an application where any force is applied perpendicular to the weak surface bond, as in the case of sliding friction, the parylene coating has a tendency to dislodge from the substrate. Also, parylene has a very low coefficient of thermal expansion. When applied to a substrate with a moderate degree of thermal expansion (i.e., stainless steel), thermal cycling can create shear stress in the already weak bonds between the parylene and the steel surface causing failure of the coating system. Parylene application sometimes requires temperatures high enough to introduce metallurgic stresses in metal substrates and cause weaknesses and physical distortions or deviation from metric specifications. Finally, parylene has a fairly low thermal limitation endpoint in that it sublimates and decomposes to the vapor monomer at low temperature [5]. Special equipment is required to produce a xylene environment for vapor deposition.
SURFACE ENERGY
Not all Solder Masks are acceptable for good conformal coating adhesion. A Surface Energy measurement is used to give an indication as to how well the conformal coating may adhere. The surface energy can be specified as a part of the circuit board surface requirement. Typical units for surface energy are Dynes per Centimeter. Coating vendors may specify or know the necessary dyne level to produce adequate adhesion. Key is to match the dyne level of the surface to the coating material.

APPLICATION TYPES
There are five main methods performed to apply the coating materials: Dip, Manual, Aerosol, Non-Aerosol, and Vapor Deposition (see figure 3). Each again has its advantages and disadvantages.

Dip application is exactly that. The circuit boards are dipped into a vat of material and allowed to drip and dry. This process is the quickest method of application but also the toughest to mask locations or connectors to prevent some seepage.

Manual application is very controllable as for location of coating (or material) but is not repeatable for thickness or prone to human error to miss locations. This is best used for reworking a location that looks to be light on coating or needs to be repaired. This can be done with a syringe or brush.

Aerosol application requires special equipment to atomize the material down to a fine mist. This allows for a very even coating but is very thin and requires multiple passes to build up the coating. This process also has a tendency to spread everywhere so an enclosed area is required to contain the process. This process is much like a paint gun using air pressure to force the material through a very small orifice.

Non-aerosol processes are very versatile to hand apply with a spray bottle or using automated spray equipment which forces the material through a needle. This application is different from Aerosol due to the fact that the material is not atomized by compression and is spread by a fan of material from the nozzle. This application applies a much thicker deposit of material.

Vapor Deposition requires some capital investment and higher maintenance for this process. The process vaporizes the materials to a cloud state. The product is held in the cloud for a certain period of time to receive the desired thickness. This again requires very good masking techniques to keep the material out of places you do not want it, similar to Dip application.

PROCESS NOTES & CONCERNS
Circuit boards should be cleaned prior to coating. Cleaning removes particulates, flux residues, oils and fingerprints which will affect coating adhesion. Cleaning can be accomplished using aqueous or solvent based chemistries. Aqueous cleaning usually contains a saponifier chemical which usually relates to higher running costs. Alcohol is another cleaning method that can also be used.

Air ionizers need to be used at all stations due to the increased generation of ESD from peeling tapes and other removable masking materials.

There are three types of curing methods that are involved with these materials: Chemical Cross linking, Heat, and UV Flash Ovens.

PROCESS DEVELOPMENT
For process setup and development, BTW, Inc. used medical industry practice of Installation, Operational, and Performance Qualification methodology.

Installation Qualification (IQ) ensures that the machine has been installed correctly and its basic functionality is present. This can be performed partially at the supplier’s location and completed on-site. This should test every feature that is standard and custom on the new or existing repurposed equipment. This is a prerequisite for Operational and Performance Qualifications.

BTW follows an IQ form that checks the standard items and leaves open other features that need to be checked. This form includes the following:

- Verify that facility hookups were correct: voltage, amperage, CFM draw for exhaust, air pressure.
- Ensures that maintenance plan is established and in system.
- Ensures that safety features are operational.
- Verify that the machine could perform basic tasks: Programming and operating software functional, communicates with network, sprays coating, control coating deposition rate.

Operational Qualification (OQ) explores the operating parameters and their interactions, limit testing, and determining allowable tolerances for key input parameters. By going through all the testing, we can use this information to setup a high performing process. This is a prerequisite for Performance Qualifications.
Performance Qualification (PQ) uses trained operators running actual product while following the limits set by the Operational Qualification to determine if key output characteristics are met consistently with high reliability and confidence. This requires actual product, and will be for that product only, unless the product is generic enough to be considered equivalent other similar product which in most cases is unlikely.

BTW'S OPERATIONAL QUALIFICATION
The OQ Plan protocol is written in advance, although not absolutely necessary. Protocol may need to deviate from plan as the process is learned. Purpose of the operational qualification is:

• To find optimum operating conditions by pushing the limits of the process
• To determine how input parameters work together to create the output condition
• To determine how tightly one must control key parameters to keep the output in the target range, i.e. process specification limits
• To learn various other techniques and intricacies of the process that are necessary to ensure an optimum result

OQ - SPRAY COATING INPUT VARIABLES
Below are our determined input parameters for Conformal Spray Coating:

• Pass Rate or Speed
• Angle
• Air Pressure
• Viscosity
• Cleanliness & Residue
• Masking
• Surface Tension and/or Roughness
• Topography

OQ - SPRAY COATING OUTPUT VARIABLES
Below are our determined output parameters for Conformal Spray Coating:

• Thickness
• Air Bubbles (“Fish Eyes”)
• Coverage
• Cobwebbing vs. Stream
• Pooling
• Adhesion

OQ – SPRAY TESTING
Figures 4, 5 & 6 are pictures of spray coverage under black lights. Multiple test runs were over Aluminum plates to simulate circuit board surface. Figure 6 is a circuit board.

OQ - MASKING TAPE TESTS
Our purpose was to determine if the masking tape varieties selected will stand up to the chemistries and adequately mask the areas necessary on the printed circuit assembly. Our method was to apply masking tapes and tape dots to circuit boards, spray with coating, and record the results.
The results are as follows (see figure 7):
- All tapes had trouble with curves.
- Tape A did very poorly to mask the coating.
- Tape C was not marginally better than A.
- Tape B and D did well to block the coating.
- All masking dots worked well.

### OQ - COATING ADHESION TAPE TESTS
Our purpose is to determine if conformal coating material adheres properly to substrate material.

For the test, we followed a simulated IPC-830 test method. Incisions were made through the material in a grid pattern. Masking tape was pressed down over cut area and then lifted in one firm stroke directly away from the substrate. Masking tape and substrate material is inspected for missing coating.

The coating adhesion tape tests passed over Aluminum. Conformal coating debris directly from the cut line where the coating was pierced was detected, but nowhere else. But note that this test only qualifies one masking type in combination with the coating material used and substrate base. If the surface/soldermask material changes, the adhesion of the coating to the substrate will need to be re-evaluated.

Since this was a generic qualification plan designed to potentially include many products, the adhesion tape test was performed on an Aluminum substrate to give a general determination that the adhesive characteristic was met.

### OQ - INVESTIGATION OF INPUTS & OUTPUTS: OVERALL METHOD
10” x 10” Aluminum coupons were sprayed at various settings for coating material viscosity, head travel speed, spray height, tank pressure, atomization spray pressure, and flow rate. After drying 24 hours, coupons were measured for coating thickness and spray pattern defects, (uneven coating, ridges, bubbles, skips, etc.). Spray pattern was monitored during the coupon spray for uniformity, cobweb creation, etc. Charts were plotted to explore the interaction and correlation of various parameters to one another.

Key Input Factors Determined:
- From figure 8 & 9, it can be seen that head travel speed and flow rate are both very influential upon coating thickness.
- Tank pressure is also influential, but on a secondary level. Tank pressure influences flow rate.
- Viscosity has counterbalancing effects: The thinner the material, the easier it flows through the valve. However, for a set flow rate, each drop of material has a lesser solids content, and, since we measure and adjust flow rate before spraying, thinner material leads only to less thickness.

### OQ - INVESTIGATION OF I/O’S: FLOW VS. THICKNESS

These charts show the linearity of the data when other factors are held constant, such as head speed and tank pressure.

### OQ - INVESTIGATION OF I/O’S: FLOW VS. TANK PRESSURE
This investigation helped determine how tightly to control tank pressure. From figure 10, slope was approximately 0.065g/5 second flow per psi – about 9% change in flow per psi change in tank pressure in the operating range. From initial setup of the equipment, tank pressure was set between 16 and 17 psi, so 1 psi = approx. 9% variation due to flow.
alone. This variation must be accounted for when setting target nominal thickness.

**OQ - INVESTIGATION OF I/O'S: SPEED VERSUS THICKNESS**

These charts (figure 11 & 12) show the strong correlation of thickness and head travel speed. Variability is due to other factors being modified in the data set, such as flow rate – another key variable.

**OQ - INVESTIGATION OF I/O'S: SPEED VERSUS THICKNESS – HOLDING FLOW RATE CONSTANT**

These charts (figure 13 & 14) show the strong correlation between thickness and head travel speed with flow rate constant.

**OQ - INVESTIGATION OF I/O'S: COMBINED FLOW RATE & SPEED VS. THICKNESS**

Concluded from previous information, flow rate is directly proportional to coating thickness and head travel speed is inversely proportional to coating thickness. So the ratio of flow rate /speed was plotted vs. thickness to determine if it is linear in the range under consideration. It was roughly linear, so an equation of the line was made in the form of $y = mx + b$ where:

- $y =$ thickness
- $m =$ slope = thickness change
- $b =$ $y$-intercept = thickness at flow rate/speed = 0 if this interaction was truly linear
OQ - INVESTIGATION OF I/O'S: VISCOSITY MEASUREMENT METHOD

Viscosity is measured using multiple methods. The quickest measurement for operators is using Zahn cups (see figure 18). These are cups with different sized holes on the bottom that can determine rough viscosity of any fluid by timing the start and end of material draining from the bottom of the cup. For this case we used #2 Zahn Cup and measured the drain time using a calibrated stop watch.

The fluid must fall within process specification limits (lift to first stream break). We used an average of 3 measurements for process control.

In early testing, viscosity was varied between 16 and 22 seconds on #2 Zahn cup (slightly outside the range of the cup). We started with 1:1 ratio by volume per HumiSeal recommendation. We settled on 16 – 17 seconds (0.95:1 ratio). We know this is out of the range of the Zahn cup but we are still using it to keep control of the HumiSeal material. A higher viscosity would lead to cobwebbing from the nozzle. Excessively low viscosity led to excessive running of material and lower thickness due to lower overall solids content percentage.

OQ - INVESTIGATION OF I/O'S: THICKNESS MEASUREMENT METHOD

Without doing cross section destructive testing or measuring with a caliper on the edges of the circuit boards, we opted to spray Aluminum metal coupons with same parameters as circuit boards we are coating. Using an eddy current thickness meter (Positector 6000), we can determine the space separation from the top of the coating to the base Aluminum (or thickness of coating). With an average and range of 10 points charted, we can conclude if the thickness is correct for a batch of circuit boards. Thickness must fall within process control limits to safely meet customer specification limits.

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**Figure 15. Flow Rate/Speed vs. Thickness with 1B73**

![Flow Rate/Speed vs Thickness (mils) - 1B73](image)

**Figure 16. Flow Rate/Speed vs. Thickness with 1B31**

![1B31 Flow Rate/Spd vs Thickness - 1B31](image)

**Figure 17. Flow Rate/Speed vs. Thickness with 1B73 Retest**

![Flow Rate/Speed vs Thickness - 3/13/12 Data - 1B73](image)

**Figure 18. #2 Zahn Cup**

![#2 Zahn Cup](image)

<table>
<thead>
<tr>
<th>Zahn Cup</th>
<th>#2</th>
</tr>
</thead>
<tbody>
<tr>
<td>Zahn Range (sec)</td>
<td>19-60</td>
</tr>
<tr>
<td>Centistoke Range</td>
<td>39-238</td>
</tr>
<tr>
<td>Applications</td>
<td>Thin Oil or Lacquer</td>
</tr>
</tbody>
</table>

See ASTM #D 4212: Viscosity by dip-type viscosity cups at 77F (25C)
OQ - INVESTIGATION OF I/O’S: FLOW TEST METHOD

In order to capture the flow rate of the spray equipment, we measure the amount of material sprayed into cup in 5 seconds. 10 individual purges of 5 seconds each are sprayed into cup to get average 5 second flow rate. This must be within process control limits to safely meet customer specification limits. We purchased a higher resolution scale (10x better – resolution 0.1g) which allows better fine tuning of flow rate to increase sensitivity of flow test resulting in less thickness variation.

PROCESS MONITORING

**Definition:** Process Monitor - The activities of consciously selecting processes, selectively and systematically observing them to compare them with others, and communicating about what has been observed to learn how to steer and shape the processes.

Processing monitoring is necessary especially on this application method to identify process drift or material issues.

Three main control charts must be watched carefully and these are:

- Thickness using eddy current meter on aluminum coupon. Average and range of 10 measurements are recorded.
- Flow Test using ten 5 second shots into a cup and recording average mass.
- Viscosity using Zahn cup average time of 3 readings.

PRIOR TO COATING

Before anything can be coated, the circuit boards have to be prepped to mask all areas of the circuit board that the customer does not want coated (i.e. grounding pad) or cannot be coated (i.e. connectors).

**Masking Tape or Dots** work very well to mask off spots on the circuit board that cannot have coating. The have a disadvantage that they cannot be used around curves or over profile parts.

**Masking Caps** is one quick method to cover connectors or large components sticking up high enough to seal the base with rubber cap. They are a lot faster than masking tape, but it does allow some seepage or wicking. Other removable sealants may to be applied around the base for extra sealing on problem areas.

**Liquid Masking** is more effective than tape dots for features with height. It is easier than tape to remove when conformal coating is wet. When using liquid masking put enough on such that it can be easily gripped with a tweezers while the coating is still wet. Advantages are no fringe of dried coating at edges and it does not tend to lift up the coating if using this method. Application time is about the same as tape (except waiting to dry).

AFTER COATING

**Forced Drying or Air Cure**

Forced oven drying drives out the solvents faster and allows faster turnaround time to second side or to next process. Also, Oven drying captures the solvent vapors and exhausts them for less overall odor creation in the coating area.

On the other hand, air drying produces fewer bubbles and lets the coating flow evenly while curing giving a smoother even look.

**Inspection**

Blacklight (UV) is required to pick up the UV tracer in the coating material. Magnification may be required depending upon complexity of the coating areas (i.e. under components).

**Figure 19. Example Inspection Sample**

PROGRAM SETUP/PROGRAMMING

When programming the spray equipment, you need to have defined rules for head travel speed and line spacing because these are highly significant factors for the final coating thickness and controlled only in the machine program.

There are two methods of programming and these are:

- Point & Teach or “bombsight” programming
- CAD data for off-line programming

**Topography**

Tall components create shadows that block the spray pattern. Use the tilt/rotate feature if you have one to spray the material at a greater angle. Use a needle dispenser to get into small spaces. Designate tough areas as “manual touchup” if you cannot coat adequately.

**Standardized Settings**

All parameters, both operator controlled parameters as well as those controlled in the spray program, that significantly influence the final coating thickness must be defined and monitored.
CLEANLINESS

Some companies spray conformal coating over no clean fluxes, but flux residues and Kapton tape residues do make a difference in the adhesion and final appearance of the product. Gloves should be worn when handling the product before and after spraying. If the flux is water soluble, the last process should be a wash followed by an adequate drying process (several options are available requiring experimentation).

PROCESS FLOW

Below are the general process steps for production through the coating process:
1. Mix and Check Viscosity
2. Setup Machine
3. Flow Test
4. Run Daily Coupon
5. Spray Circuit Board Side 1
6. Let Dry to Touch
7. Inspect and Touch-up as Needed
8. Spray Circuit Board Side 2
9. Let Dry to Touch
10. Inspect and Touch-up as Needed
11. Let Air Dry for 24 Hours
12. Measure Coupon Process Monitor
13. Release Job based on Process Monitor

DAILY SETUP/CLEANUP STEPS

Setup Steps
1. Mix material and verify viscosity
2. Set tank pressure
3. Perform flow test and adjust flow rate
4. Affix air cap to nozzle
5. Set spray pressure
6. Run daily test coupon (for thickness verification after dry)
7. Set up fixtures for board to be run
8. Load program and run

This averages about 30 – 40 minutes for one machine and associated area around the process.

Cleanup Steps
1. Remove material from tank and purge lines
2. Load solvent into tank and run through lines, purge several times
3. Remove solvent from tank and purge lines until air runs free
4. Clean up touchup/inspection station – put away all materials
5. Sweep floor

This averages about 20 minutes for one machine and associated area around the process.

CONCLUSION

Going back to the beginning, you need to follow these steps to develop the conformal coating process:
- Determine what you are trying to protect the assembly from and which materials support this need.
- Determine the surface energy of the assembly to ensure that the assembly can be coated.
- Develop the Requirements
  - Required thickness
  - Keep out areas
  - Materials
  - Acceptance criteria
- Develop the Process
  - Spray Patterns, Dip or Manual Steps
  - Tooling (Pallets, Special Nozzles, Brushes, etc.)
  - Machine Programs
  - Cure Process & Times
  - Viscosity
  - Test Coupons
  - Temperature & Humidity Controls
- Clean the assembly?
- How to mask non-coating areas?
- How to apply coating?
- How to cure coating?
- Unmask board before or after curing?
- What about repair/touchup?
- Inspection method?
- Process control methods?

And lastly: Keep consistent controls of the process!

ACKNOWLEDGEMENTS

The author would like to thank Dave Jensen for his contribution toward this presentation/paper. Also, the author would like to acknowledge the support of BTW, Inc. for travel and time away from the office for this paper and presentation.

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