Designing Polymer Molecular Structure for Conformal Coating for Optimized Printed Circuit Board Protection Against Outdoor and Extreme Elements

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ABSTRACT

With the advance of microelectronics in everyday life, a growing number of sensors, processors, and communications equipment operate in severe environments. Aeronautic, maritime, and industrial electronics face harsh operating conditions and a large and increasing amount of commercial electronics such as LED displays and automotive electronics are used outdoors. Advanced protective coatings that can be applied cost effectively are needed for the long-term life and reliability of these microelectronics.

This paper examines the challenges facing traditional types of conformal coatings and reviews coating attributes such as adhesion, moisture resistance and barrier, corrosive gas barrier, prevention of ionic migration and environmental stress-crack that must be improved to improve reliability of electronics under severe conditions. The ever-important factors of ease of use and cost in addition to performance are also compared and considered.

AI Technology introduces two new types of conformal coatings that are qualified under the IPC-CC-830C standards of testing and meet the Mil-Std requirements of MIL-I-46058. The key difference in these new types of conformal coatings is the ability to block moisture and corrosive gases in combination with hydrophobicity for unparalleled conformal circuit protection. Both types of conformal coatings can be applied with standard spray-dip-brush methods and air dry at ambient temperature for thickness of 15-50 microns and “Parylene type” performance.

INTRODUCTION

Conformal coatings of various types have been used in protecting printed wiring boards (PWB), high reliability electronics, and exposed electronic systems for decades. However, protecting advanced electronics is more challenging than ever before. Electronic devices are increasingly used outdoors and incorporated extensively in commercial electronics such as vehicles and ubiquitous communication base stations. The requirements for conformal coatings also grow more demanding with finer pitch and spacing in contemporary systems. Such systems include today’s high frequency devices; with device components in closer proximity than previously, new and growing challenges emerge for conformal coatings. Existing types of conformal coatings have proven to sometimes not meet the more stringent requirements of outdoor use, which may include high moisture, temperature extremes, salt or corrosive industrial gas laden conditions. The proliferation of electronics facing these extreme conditions demands a new type of stress-free conformal coating with far superior moisture and corrosive gas blocking ability to provide protection and ensure reliability.

Figure 1: Outdoor digital LED and Micro-LED displays, automotive electronics and autonomous vehicles represent some of the challenging electronics and printed wiring boards to protect under extreme outdoor conditions

The basic function for conformal coatings on PWB or PCB (printed circuit board) is to provide higher reliability and longer operation life for the electronic device under different environments. This includes providing protection against the following environmental factors:

1. Moisture ingression
2. Salt-fog ingression
3. Fungi attack

IPC-CC-830C qualifications provide standards of testing against such environmental factors and separately, specifications for electrical insulation. Users must test conformal coatings under the actual usage and operating conditions for their specific applications as outlined below.

- Larger circuit boards mounted with high profile components: Larger area circuit boards induce greater interfacial stress with differential thermal expansion between the board and higher rigidity conformal coatings. Boards with multiple high-profile components introduce corresponding points of stress concentration. Extreme temperature excursions cause the more rigid and non-compliant conformal coatings to crack and delaminate.
- Operating outdoor and in extreme environments: For outdoor applications, exposure to industrial gases such as hydrogen sulfide, sulfur dioxide, nitric oxide, carbon dioxide and chlorine is unavoidable. When coupled with high moisture the degradation to the circuit boards may be accelerated, especially for those circuits with finer pitch and spacing.
- Operating under more extensive temperature cycling, shocks and other stresses: Aeronautic electronics are exposed to fast compression and decompression along with extreme temperature swings during landing. Automotive electronics are commonly exposed to low temperatures in northern geographies and quickly rise in temperature after starting. Automotive electronics, digital displays, cellular base stations operating near the coastal areas and marine electronics are exposed to extensive salt-fog and even salt-spray.

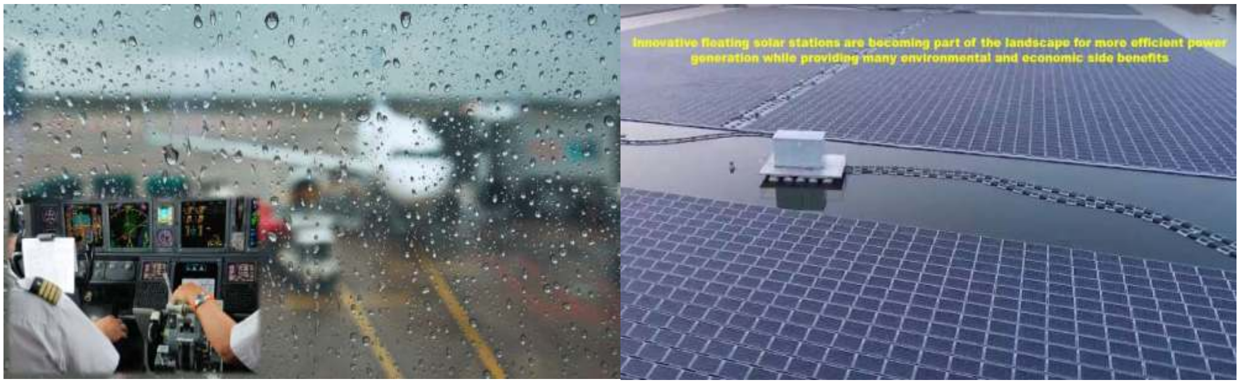

Figure 2: Aeronautic electronics and innovative power stations over water require cost effectiveness and higher protection performance beyond traditional conformal coatings

MOISTURE PERMEATION-BARRIER IS MUCH MORE IMPORTANT THAN LOW MOISTURE ABSORPTION AND HIGH HYDROPHOBICITY

BEING HYDROPHOBIC IS NOT ENOUGH FOR CONFORMAL COATINGS: Much of the promotional information for conformal coatings emphasize the importance of their hydrophobic properties and not their ability to block or prevent moisture from permeating through the thin coating layer.

Hydrophobicity is typically demonstrated with “balling up” or high contact angle when water droplets are placed on top of a conformal coating surface. The hydrophobic characteristic is a result of the incompatibility of low surface energy and non-polar nature of the conformal coating and the high surface energy of polar water droplets or water spray.

Hydrophobic characteristics are good for repelling water droplets and even short-term water immersion. However, among conformal coatings, silicone is the worst in moisture barrier and allows the highest rate of moisture penetration despite its unparalleled hydrophobic nature. Silicone based conformal coating has been reported in many studies to have the worst performance in high humidity and warm climate conditions.

The reason is that silicone conformal coating, even at the relative higher thickness used in protecting circuit boards, still exhibits the highest moisture permeability through the coating and forms water molecules along the coating and board interfaces. The difference between hydrophobicity and permeability of silicone polymers used as conformal coating are not well understood by most that are tasked to provide protection to the circuit boards.

The ideal conformal coating is one that blocks moisture and other corrosive gaseous molecules from permeating through the thin coating while still being hydrophobic. This requires molecular engineering of the polymer structure for use as conformal protective coating for circuit boards.

Figure 3: Illustration[1] *of difference in surface energy of substrate (non-polar to polar) to water droplets (polar). Hydrophobic conformal coatings may have dramatic difference in moisture permeability. It is critical that hydrophobic conformal coatings be coupled with high moisture barrier (low moisture permeability) to be effective in protecting printed circuit boards.*

WATER ABSORPTION INSIDE CONFORMAL COATINGS IS NOT THE ONLY PROBLEM: Water absorption inside any specific polymer, including typical acrylic, silicone, epoxy, polyurethane, and Parylene based conformal coatings, is mostly a reflection of the polarity of the polymer molecules. Water is polar in molecular structure. As such, it has an affinity to polar polymers.

Silicone polymers typically have very little affinity to water. However, they have one of the highest permeabilities for moisture and corrosive gases, allowing penetration onto the interfaces of the printed wiring boards the coating is trying to protect; this causes corrosion and defects.

In applications, acrylic based coatings absorb several times more water by weight percentage than silicone based coatings. However, because the rate of water molecule penetration in silicone types is two or more orders higher and the water molecule retention beneath silicone based coatings is greater, they are typically outperformed by the acrylic types in protecting PWB against corrosion; this is a contributing factor to acrylic types' hold on a larger market share.

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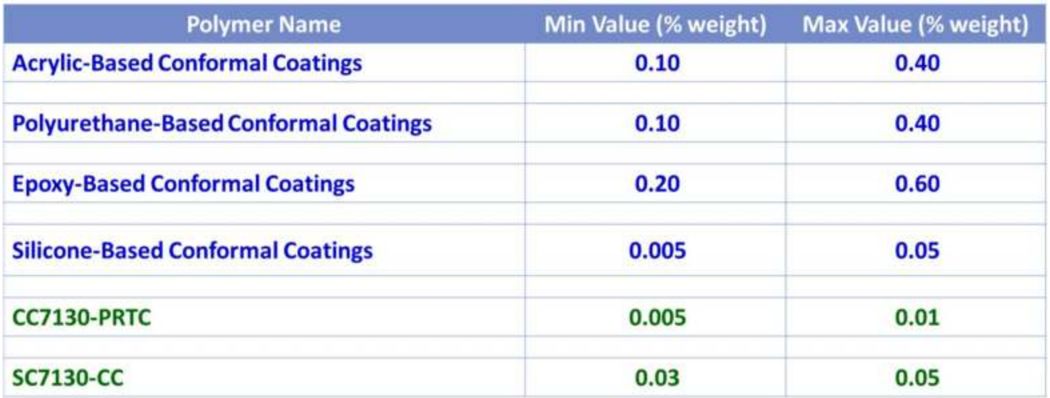
[1] https://www.detailingwiki.org/detailing-miscellaneous/what-is-hydrophobic/attachment/hydrophilic-versus-hydrophobic/ https://all-free-download.com/free-photos/download/wizard-clear-water-droplets-02-highdefinition-picture_166218.html

The following is a tabulation of literature results of maximum and minimum weight % of water absorption[2] [3] with additional data of conformal coatings recently tested by a certified independent laboratory based on IPC-CC-830C specification.



Polymer Name	Min Value (% weight)	Max Value (% weight)
Acrylic-Based Conformal Coatings	0.10	0.40
Polyurethane-Based Conformal Coatings	0.10	0.40
Epoxy-Based Conformal Coatings	0.20	0.60
Silicone-Based Conformal Coatings	0.005	0.05
CC7130-PRTC	0.005	0.01
SC7130-CC	0.03	0.05

Table 1: A tabulation of water absorption for some of the common conformal coating types. While acrylic based and polyurethane based conformal coatings tend to be more polar and retain more water under the same condition of temperature and humidity, in most cases, they perform better in protecting electronic circuit boards with 75 microns, compared to 200 micron thick silicone conformal coating. CC7130-PRTC and SC7130-CC combine low water absorption and high moisture and harmful gas barrier capability to achieve the highest printed circuit board protection at thickness of 50 µm to less than 12.5 µm.

MOISTURE PERMEABILITY: THE INABILITY TO BLOCK OUT MOISTURE PENETRATION IS THE BIGGEST PROBLEM IN CONFORMAL COATING: Moisture permeability is significantly more important to a thin conformal coating on a PWB than the coating's moisture absorption.

A conformal coating's moisture permeability, or transmission rate, varies drastically because of molecular conformational and packing structure[4], affinity to water moisture, and temperature dependence. In phenomenological terms of polymeric structure, permeability is described by volume of free-space (**free space volume**) and the **average size of molecular free-space, or pore**.

The ideal conformal coating molecular structure should be engineered to have low free-space volume and small pore size to limit the penetration by moisture. Such coating should also have very little affinity to absorbing water within the coating and be as hydrophobic as possible.

The following pictorial representation of "free space" and "average pore size" describes part of the complex dependence[5] of typical polymers. Rigid conformal coating, such as acrylic based,

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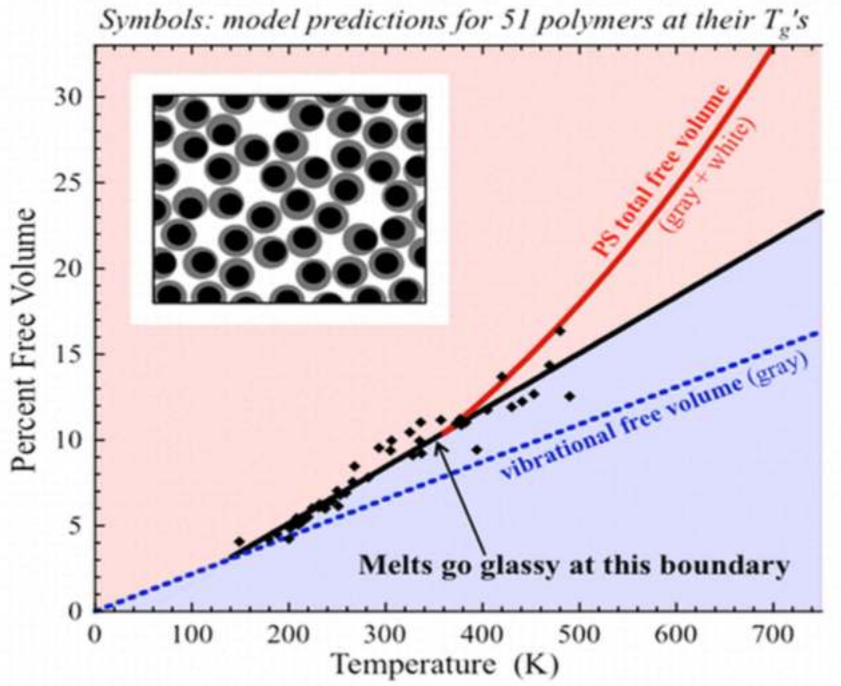
[2] https://imageserv5.team-logic.com/mediaLibrary/99/D116_20Haibing_20Zhang_20et_20al.pdf

[3] https://omnexus.specialchem.com/polymer-properties/properties/water-absorption-24-hours

[4] https://en.wikipedia.org/wiki/Flory%E2%80%93Fox_equation

[5] Polymer Free Volume and Its Connection to the Glass Transition, by Ronald P. White and Jane E. G. Lipson* *Macromolecules* 2016, 49, 11, 3987-4007https://doi.org/10.1021/acs.macromol.6b00215

has glass transition temperature (Tg) above ambient and thus smaller pores and lower volume of free-space. Silicone polymers have a Tg well below ambient have much greater free-space volume.



Polymer Free Volume and Its Connection to the Glass Transition

•Ronald P. White
•Jane E. G. Lipson*
Macromolecules 2016, 49, 11, 3987-4007
Publication Date:May 23, 2016
https://doi.org/10.1021/acs.macromol.6b00215

Figure 4: The temperature dependence of polymer free space volume is a combination of the atomic vibrational free volume, molecular conformation and molecular packing free volume. The total free volume and the average size of free space pore determines the transmitting rate or permeability of the conformal coating. Higher temperature above glass transition increases the total free volume and the average free space pore for higher moisture and harmful gas diffusion rate into the interface between the circuit board and the conformal coating.

For example, silicone's molecular structure is non-polar and thus it has low affinity to moisture or water molecules. But silicone conformal coating generally has higher volume of free-space and large pore size and therefore a higher coefficient of water permeability[6]. This allows moisture to penetrate and collect on the interface between the silicone conformal coating and PWB. As a result, it has the least ability to prevent moisture from penetrating the conformal coating and reaching the PWB by several orders of magnitude.

Acrylic based conformal coatings tend to have Tg above ambient and thus better prevent moisture penetration through the conformal coating. Polyurethane and epoxy based conformal coating have a similar order of permeability, as illustrated below. The highlighted range of water (moisture) permeability is provided by the authors.

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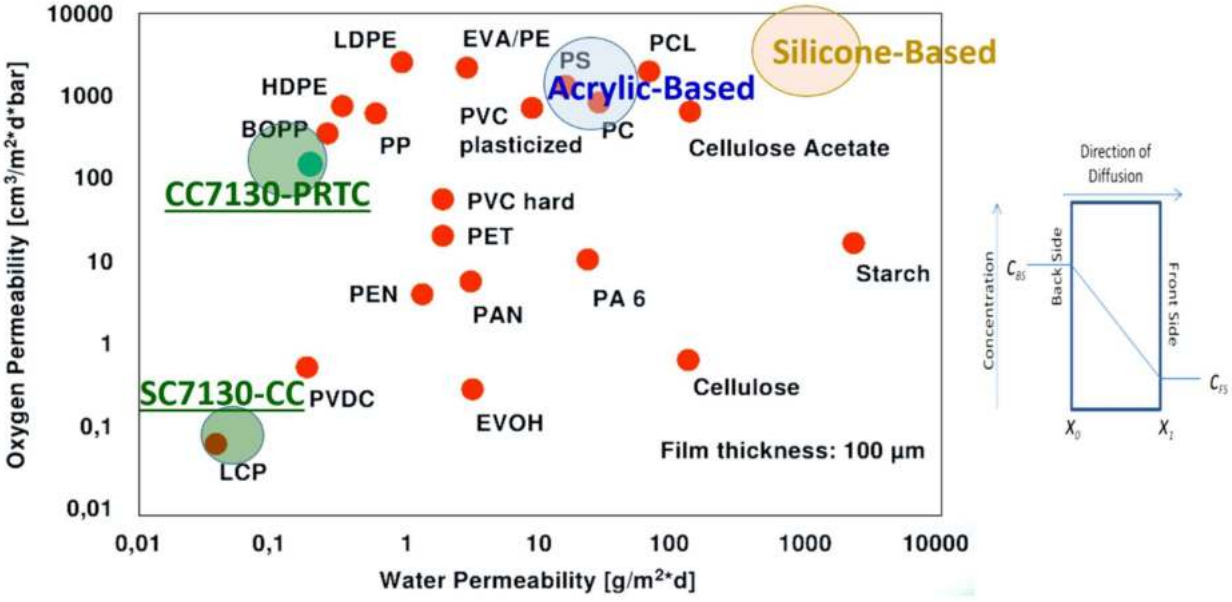
[6] https://imageserv5.team-logic.com/mediaLibrary/99/D116_20Haibing_20Zhang_20et_20al.pdf



https://www.slideshare.net/TopasAdvancedPolymers/high-aroma-barrier-films-for-food-packaging

Figure 5: A plot of some common polymers including those commonly used to constitute the conformal coatings film. Moisture and harmful gases diffuse from high humidity and higher concentration into the interface between the printed circuit board and the conformal coating. Fickian Diffusion is used to describe the permeability such as water and other harmful gases. The coefficient of diffusion or permeability is a phenomenological summary of the effects of the free space volume and average size of the free space pore. CC7130-PRTC and SC7130-CC have been engineered to have molecular structures that combine the low water absorption and high moisture and corrosive gas barrier to achieve the highest printed circuit board protection even at thickness of typical vacuum deposited Parylene at 50µm to less than 12.5 µm.

Moisture permeability does not depend solely on the glass transition temperature (Tg) and molecular conformation or rigidity of the polymers. Different polymer molecular structures are dramatically different in water permeability; some are better than others. For example, PET has significantly lower moisture permeability when compare to acrylic, epoxy and polyurethane. Saran (PVDC) food protection film and Polyethylene films tend to have moisture barrier ability although they are both flexible with Tg well below -40°C.

The highlighted moisture permeability of CC7130-PRTC[7] and SC7130-CC[8] are a result of the engineered high moisture barrier molecular structure and lowest moisture permeability for polymeric coating. CC7130-PRTC and SC7130-CC engineererd structures are modified ethylene and fluorinated polymers respectively. Details of these conformal coating used for PWB protection will be presented in the latter part of the paper.

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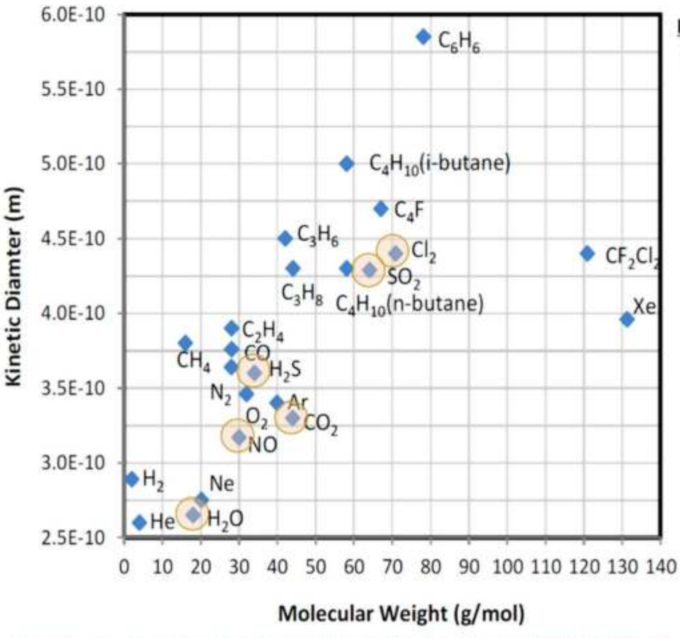
[7] NTS Test Report No. PR107890-00 Part 2 of 2 (Available with non-disclosure agreement only)

[8] NTS Test Report No. PR107890-00 Part 1 of 2 (Available with non-disclosure agreement only)

DIFFUSION OF HARMFUL GASES THROUGH CONFORMAL COATINGS DEGRADE PWB[9] [10]

The ability to penetrate a conformal coating or any thin plastic differs due to the individual molecular structure dictating overall free space volume and pore sizes. Permeability or diffusion of any specific gas is typically described by the Fickian diffusion coefficient and thickness at any specific temperature[10].

The rate of diffusion for a polymer coating, with its specific free space volume and pore sizes, will differ for various gases. The rate of diffusion for each specific gas is dependent its “kinetic diameter”, defined by the size of the gas molecules. The smaller the kinetic diameter, the faster and easier it can penetrate through the conformal coating. The penetration of moisture (water in gas state), nitrogen oxide, carbon dioxide, hydrogen sulfide, sulfur dioxide, and chlorine are of particular importance in the context of conformal coatings because of their damaging effects on copper and tin metallization, commonly utilized on printed boards. The highlighted elements are made by the author.



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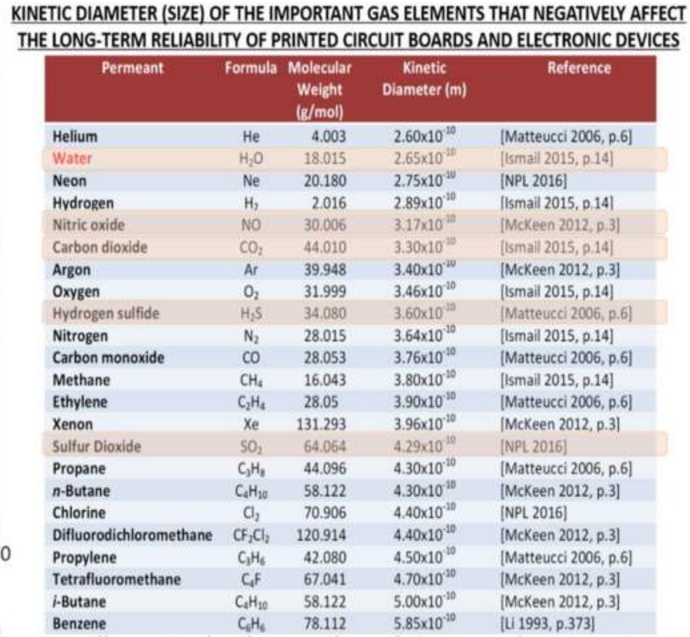

KINETIC DIAMETER (SIZE) OF THE IMPORTANT GAS ELEMENTS THAT NEGATIVELY AFFECT THE LONG-TERM RELIABILITY OF PRINTED CIRCUIT BOARDS AND ELECTRONIC DEVICES

Permeant	Formula	Molecular Weight (g/mol)	Kinetic Diameter (m)	Reference
Helium	He	4.003	2.60×10^{-10}	[Matteucci 2006, p.6]
Water	H_2O	18.015	2.65×10^{-10}	[Ismail 2015, p.14]
Neon	Ne	20.180	2.75×10^{-10}	[NPL 2016]
Hydrogen	H_2	2.016	2.89×10^{-10}	[Ismail 2015, p.14]
Nitric oxide	NO	30.006	3.17×10^{-10}	[McKeen 2012, p.3]
Carbon dioxide	CO_2	44.010	3.30×10^{-10}	[Ismail 2015, p.14]
Argon	Ar	39.948	3.40×10^{-10}	[McKeen 2012, p.3]
Oxygen	O_2	31.999	3.46×10^{-10}	[Ismail 2015, p.14]
Hydrogen sulfide	H_2S	34.080	3.60×10^{-10}	[Matteucci 2006, p.6]
Nitrogen	N_2	28.015	3.64×10^{-10}	[Ismail 2015, p.14]
Carbon monoxide	CO	28.053	3.76×10^{-10}	[Matteucci 2006, p.6]
Methane	CH_4	16.043	3.80×10^{-10}	[Ismail 2015, p.14]
Ethylene	C_2H_4	28.05	3.90×10^{-10}	[Matteucci 2006, p.6]
Xenon	Xe	131.293	3.96×10^{-10}	[McKeen 2012, p.3]
Sulfur Dioxide	SO_2	64.064	4.29×10^{-10}	[NPL 2016]
Propane	C_3H_8	44.096	4.30×10^{-10}	[Matteucci 2006, p.6]
***n*-Butane**	C_4H_{10}	58.122	4.30×10^{-10}	[McKeen 2012, p.3]
Chlorine	Cl_2	70.906	4.40×10^{-10}	[NPL 2016]
Difluorodichloromethane	CF_2Cl_2	120.914	4.40×10^{-10}	[McKeen 2012, p.3]
Propylene	C_3H_6	42.080	4.50×10^{-10}	[Matteucci 2006, p.6]
Tetrafluoromethane	C_4F	67.041	4.70×10^{-10}	[McKeen 2012, p.3]
***i*-Butane**	C_4H_{10}	58.122	5.00×10^{-10}	[McKeen 2012, p.3]
Benzene	C_6H_6	78.112	5.85×10^{-10}	[Li 1993, p.373]

Figure 6 and Table 2: Highlighting the kinetic diameters of the common harmful gases such as water, nitric oxide, carbon dioxide, hydrogen sulfide, sulfur dioxide and chlorine. Smaller kinetic diameter penetrates easier for a specific polymer with specific free space volume and average free space pore size. Higher temperature, particularly above glass transition temperatures increases the free space volume and average pore size and thus facilitate the harmful gases penetration into the PWB and conformal coating interface.

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[9] The Role of Permeability and Ion Transport in Conformal Coating Protection, by A MENSAH and C HUNT file:///C:/Users/kchung/Downloads/The_Role_of_Permeability_and_Ion_Transport_in_Conf.pdf

[10] https://www.pnnl.gov/main/publications/external/technical_reports/PNNL-26070.pdf

The combination of water and the other harmful gases can form acidic and ionic molecules that cause corrosion and shorting of the circuit traces.

The following is an illustration of silicone conformal coating corrosion. In this cited study and many others similar studies, silicone conformal coating results in the highest corrosion among all of the conformal coating types[11] even though it is by far the thickest among all coatings. This specimen was exposed to active damaging gases alongside moisture.

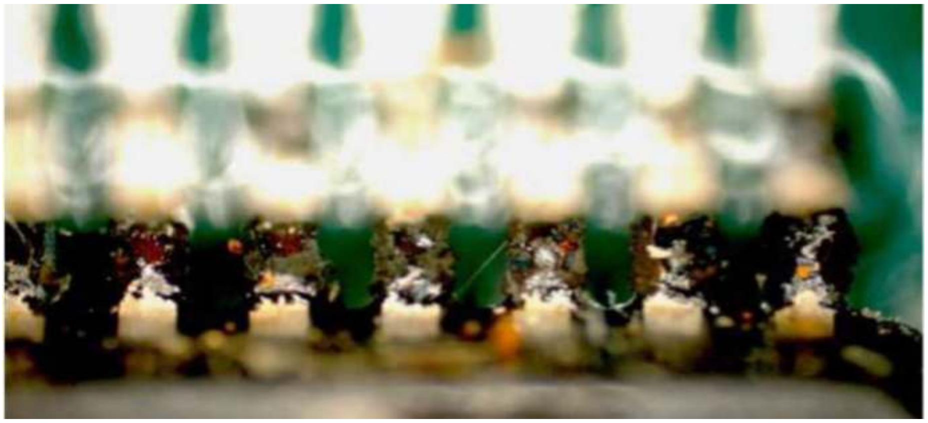

Figure 7: The highest corrosion occurred when harmful gases were combined with high moisture penetration through the thick layer of silicone conformal coating in this study by Osterman[11].

A new type of proposed vacuum deposited aluminum oxide "ultra-thin" conformal coating, surprisingly showed the second worst corrosion results under the same test condition.

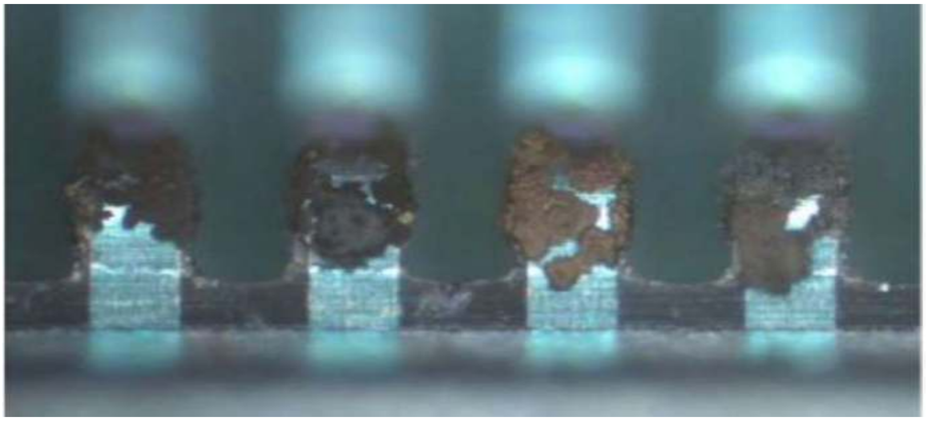

Figure 8: The second worst corrosion occurred when harmful gases were combined with high moisture through the ultrathin aluminum oxide layer vacuum deposited as conformal coating in this parallel test. Study by Osterman[11].

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[11] Effectiveness of Conformal Coat to Prevent Corrosion of Nickel-palladium-gold-finished Terminals by Michael Osterman, http://www.circuitinsight.com/pdf/effectiveness_conformal_coat_prevent_corrosion_nickel_palladium_gold_ipc.pdf

SALT-FOG AND SALT-SPRAY INDUCED PRINTED CIRCUIT BOARD FAILURES

Salt-spray protection requirements are common for electronics operating near sea coasts and are much more stringent than salt-fog requirements for protective coatings. The ionic migration and degradation effects on the underlining circuit impedance may be analyzed using "Electrochemical Impedance Spectroscopy" test results [12]. FEVE is not used for conformal coating. It is a specially developed fluorinated cross-linked coating used to protect bridges operating over sea and salt-spray environments.

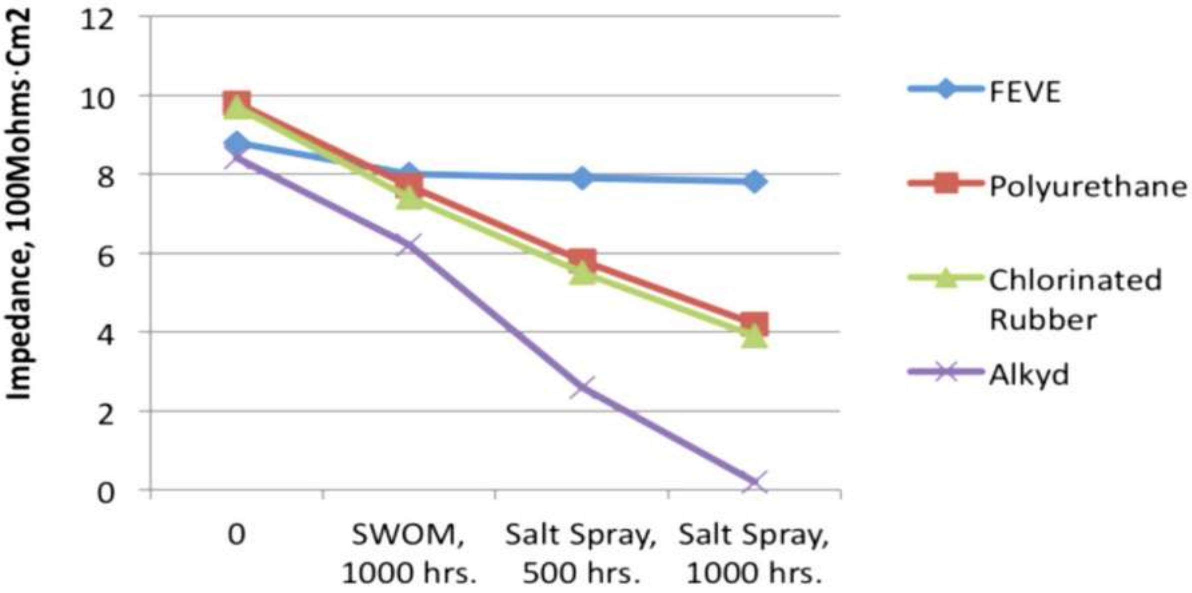

Figure 9: A plot of electrical impedance degradation when several polymers used in bridge coating protection are exposed to salt-spray to simulate the operating condition over seawater[12]. In this particular study FEVE is a fluoroethylene vinyl ether resin-based cross-linked powder coating and provides the best protection. Polyurethane is a cross-linked "rubber" similar in performance to chlorinated rubber coating. While Alkyd has mechanical properties similar to epoxy, it performed the worst over long period of salt-spray.

From the above study, it is obvious that some polymer molecular structures are more resistant to salt-spray than others. This represents the ionic migration resistance afforded by different polymer structure. The same characteristics also provide corresponding protection in the case of conformal coatings protecting PWB.

Salt-spray testing, while not used in the IPC-CC-830C qualifications, is an effective test to distinguish whether a conformal coating is adequate to protect the PWB under the long-term exposure to environments near the sea. This stringent testing with salt-spray (simulating extreme salt-fog with condensation) on PWB applies not only to marine electronics, it also applies to aeronautic, industrial, maritime and automotive electronics. SC7130-CC is modified

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[12] https://www.aisc.org/globalassets/nsba/conference-proceedings/2018/2018-wsbs-final-paper---darden.pdf

and engineered fluorinated conformal coating that has been tested by aeronautic users to have an unparalleled advantage over the acrylic conformal coating for the applications based on Radio Technical Commission for Aeronautics (RTCA DO 160).

The leads and components on high frequency devices produce the electric field that drives the migration of ions. In 5G devices, the proximity between leads and components is extreme; the electric field responsible for transporting water born ionics is stronger than previous devices under the same voltage. With the rise of 5G, the ability for a conformal coating to prevent ionic migration is more important than ever before.

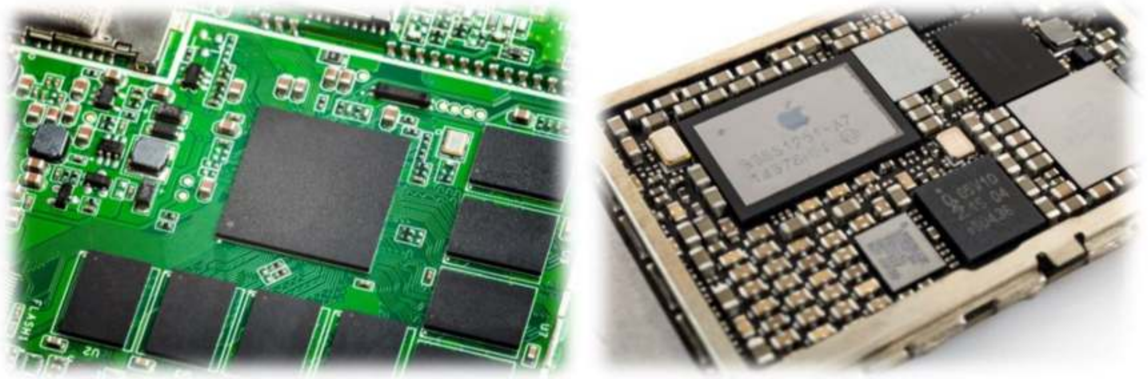

Figure 10: Printed circuit boards used in higher frequency electronic devices need to have much closer proximity to each other besides having finer pitches to optimize the performance. Under the same voltage, the electric field that drives the mobility of ions such as salt and acidic solutions of harmful gases also increases. Thus, suitable conformal coating needs to be thin while still protecting the metal traces from corrosions.

STRESS CRACKING COUPLING WITH ENVIRONMENTAL FACTORS ACCELERATE REAL-LIFE CONFORMAL COATING FAILURES

In all electronic conformal coating and packaging applications, interfacial stress and stress concentration are two of the most important considerations for long-term reliability. In the case of conformal coatings these stresses may be induced from temperature excursions under normal operating conditions different from the coating curing temperature. The printed circuit board substrate is a fiber-glass reinforced epoxy with controlled planar coefficient of thermal expansion (CTE) of 16-20 ppm/ºC[13] to match that of the copper traces used to build the interconnection. In controlling the planar CTE, the Z-axis CTE is >70 ppm/ºC.

Conformal coating is typically applied as air-dry or vacuum deposited onto the PWB at ambient temperature. CTE is in the range of 55-65 ppm/ºC for acrylic and epoxy based types, and 35 ppm/ºC for the Parylene type. The differential CTE causes strain in the conformal coating bonding onto the stronger PWB and thus induces stress on the conformal coating and stress concentration at sharp interfaces such as around components and solder joints. In simple

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[13] https://smtnet.com/library/files/upload/PCB-Heat-Challenges.pdf https://en.wikipedia.org/wiki/FR-4

terms, the stress induced on the conformal coating increases with increase in differential CTE, compressive stress increases with temperature excursion below ambient, and tensile stress increases with temperature excursions above ambient. The compressive and tensile stress and the stress concentration also increase with higher modulus of conformal coating. Sometimes thousands of psi stress are induced. This stress may cause cracks, from micro-and-hairline to large cracks, or even delamination of the conformal coating.[14]

Figure 11: Representation of conformal coating protecting PWB with multiple components and solder joints. Besides having ability to prevent penetration to the PWB by moisture-water and harmful gases, the conformal coating must also withstand thermal cycling and thermal shock induced interfacial stress and stress concentration at corners and solder joints.

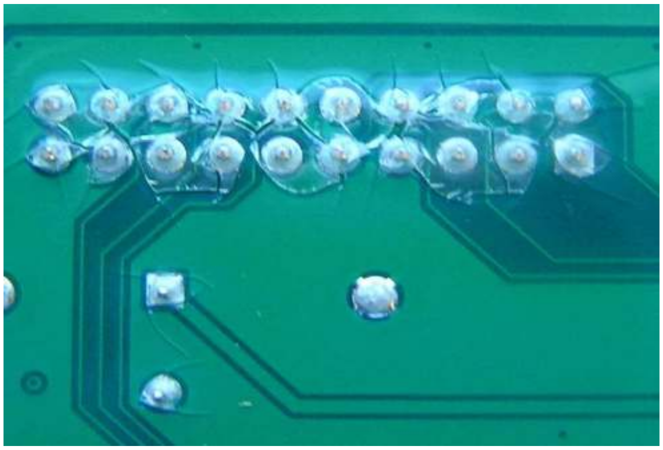

Figure 12: Picture of cracks and delamination of conformal coating from PWB and solder joints[15] where stresses are more concentrated.

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[14] Chung, et. al. http://www.aitechnology.com/uploads/pdf/WHITE%20PAPER/lowTgEpoxy.pdf

[15] http://www.conformalcoatinghelp.com/wp-content/uploads/2016/02/Conformal-coating-cracking-640.jpeg

The following is a pictorial representation of the factors that induce tensile and compressive stresses along with stress concentration at sharp corners.

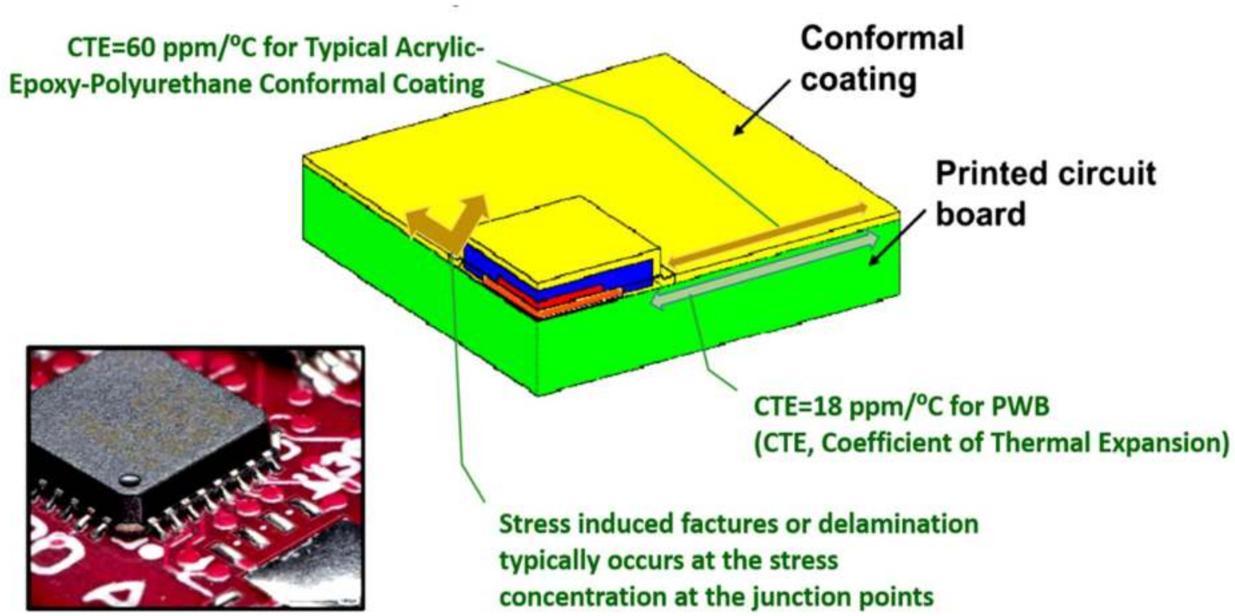

Figure 13: Representation of conformal coating protecting PWB as illustrated by Vianco[16]. This particular PWB has a soldered QPFN to illustrate the 3D aspects in stress consideration. The CTE aspects illustration of the stress consideration is added by the author. Parylene has lower CTE of 35 ppm/ºC[17] that is still substantially different from 18 ppm/ºC of PWB and copper traces.

To manage the shear stresses and stress concentration without the ability to match the CTE, the conformal coating should be low in modulus and have the capability to stretch. Silicone conformal coating, although lacking in ability to block moisture and harmful gases, is flexible and low in modulus and thus normally will not fail due to stress.

CC7130-PRTC and SC7130-CC have been molecularly engineered to have low modulus and high flexibility as not to induce shear, compressive stresses, and stress concentration.

EASE TO AUTOMATE, FIELD APPLICABLE AND COST EFFECTIVENESS OF CONFORMAL COATING

COMPLICATED PROCESSING OF VACUUM DEPOSITION IS A LIMITATION: One of the main reasons that acrylic conformal coatings, even with their limitations, are still the predominate type used over Parylene conformal coatings is their relative low material and application cost. Parylene conformal coating requires vacuum deposition processes and small batch size limitations prevent its use in more commercial applications. Similar limitation may also apply to the new type of “ultra-thin, UT” conformal oxide coating that is deposited under vacuum.

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[16] Computational Models: A Critical Enabler of Advanced Electronic Packaging for Use in High-Reliability Applications, Paul T. Vianco https://www.osti.gov/servlets/purl/1507040

[17] https://www.advancedcoating.com/thermal-properties

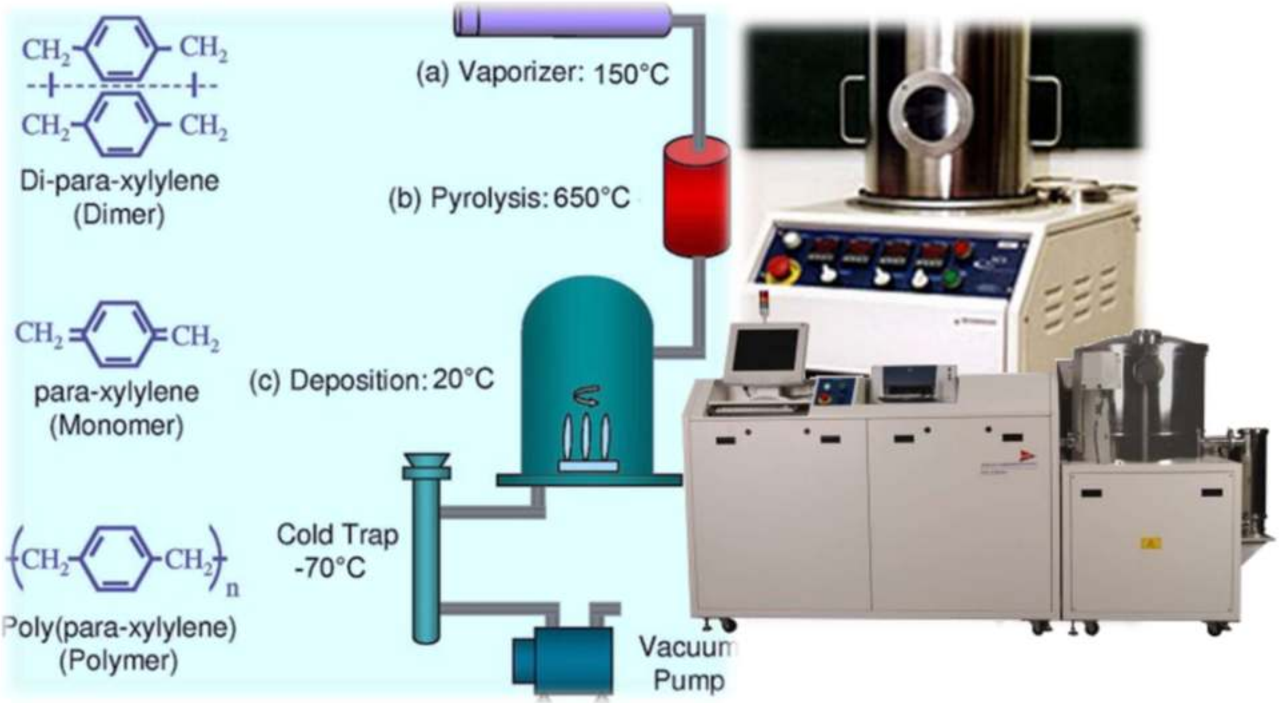

Figure 14: Parylene and the proposed ultra-thin oxide conformal coatings have to be deposited under stringent vacuum and temperature conditions. Not only raw material costs are substantially higher for Parylene, the application process cost and time are also limitations.

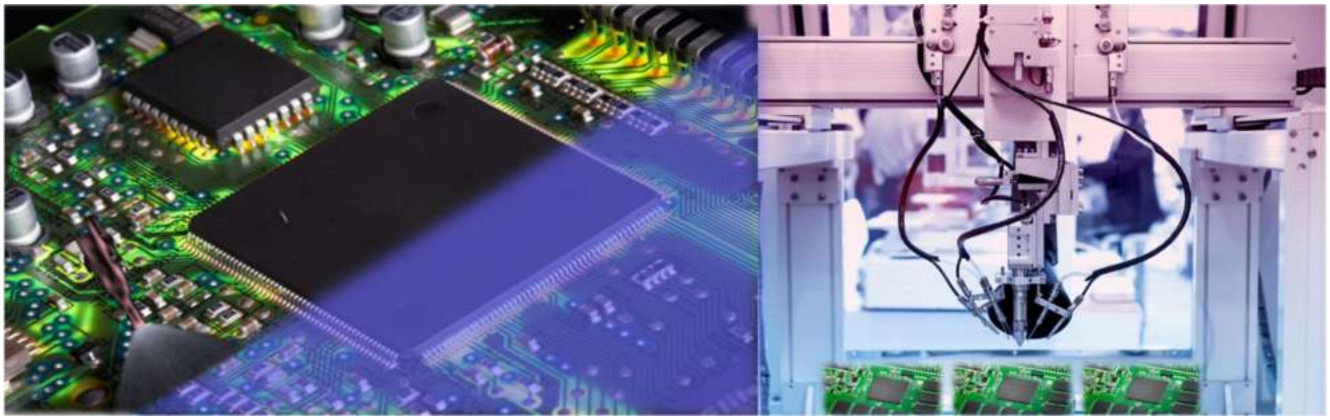

Figure 15: SC7130-CC and CC7130-PRTC are engineered to use industrial standard spray-dip-brush method to deposit 12.5 µm to 50 µm (average of 20-40 µm) air dry film on PWB. The overall usage costs are comparable to acrylic conformal coatings while providing protection equal to and sometimes better than Parylene conformal coating. They are particularly suitable for densely populated PWB with no limitation on circuit board size and high volume of production. Besides being repairable, they are also field applicable with no VOC limitation.

CONCLUSION:

Today's advanced electronics require protection to ensure the highest reliability even in extreme conditions. Their operational environments may expose electronics to high humidity, salt-fog and salt-spray, temperature variance or even thermal shock, and industrial atmosphere laden with corrosive gases like sulfur dioxide, hydrogen sulfide, nitrogen dioxide, etc. Millimeter frequency devices, like those used with 5G, feature fine-pitch components and leads separated by smaller, ever closing distance, creating a greater need for prevention of ionic migration. This protection must be cost effective and possess convenient ease of application for use in large scale electronic manufacturing used by large swaths of modern commercial electronics.

As none of the existing types of conformal coatings meet this list of requirements, new types of conformal coatings are necessary. These new types of conformal coatings must be easy to deposit and cost effective but with the same or better performance than those deposited under stringent controlled vacuum and temperature conditions such as Parylene.

New and improved types of conformal coatings must meet the technical challenges of difficult operating conditions including at least the following:

1. Barrier to prevent penetration of moisture laden with active gases such as hydrogen sulfide, sulfur dioxide, carbon dioxide, and nitrogen dioxide that may become trapped as weak acidic solution at the interface between conformal coating and PWB.
2. Barrier to ionic migration in salt-spray and salt-fog, such as required in automotive, industrial, maritime, and aeronautic electronics.

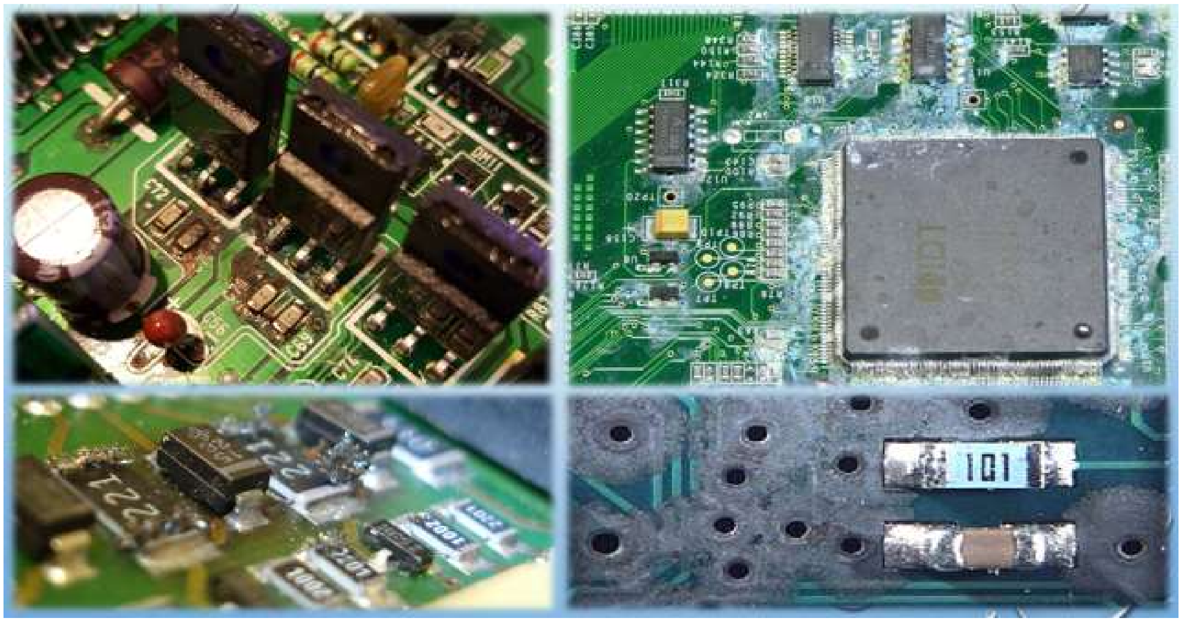

Figure 16: Ionic and acidic ingression from salt-fog-spray and industrial gases such as hydrogen sulfide and sulfur dioxide, nitric oxide, etc. all require high moisture penetration barrier and prevent accumulation of these corrosive mixture at the PWB and conformal coating interface.

(3) Flexibility - low modulus with high capability to stretch.
   - Flexibility is required to absorb thermal excursion induced interfacial stresses due to the mismatches between tough and high strength conformal coatings with CTE of ~60 ppm/ºC (acrylic and epoxy type) or 35ppm/ºC (Parylene type) and 18 ppm/ºC of PWB and copper traces.
   - Must have the molecular flexibility to absorb and prevent interfacial stresses and stress concentration due to rapid compression and decompression coupled with temperature shock excursions in aeronautic electronics.

(4) While some vacuum deposited conformal coatings such as Parylene have been proven to perform better than typical acrylic types with thinner coating 12.5 µm to 50 µm coating, the high cost and volume production limitations make their use in wider commercial electronics difficult. The new types of conformal coating preferably utilize low cost spray-dip-brush deposition method and yet provide Parylene performance in protection with similar thin coating. Ideally, the new solution will improve over Parylene type coating with lower interfacial stress and the ability to repair when needed.

**IPC-CC-830C CERTIFIED SPRAY-DIP-BRUSH CONFORMAL COATINGS:
MOISTURE AND HARMFUL GASES BLOCKING PERFORMANCE**

☐ SC-7130-CC: MEETS AND EXCEEDS ALL "PARYLENE" CLASS PERFORMANCE
  - PROVEN UNPARALLELED PERFORMANCE FOR AERONAUTIC ELECTRONICS, DIGITAL DISPLAYS IN PROTECTING AGAINST SALT-SPRAY, SALT-FOG AND ACID RAIN EXPOSURE
  - MOLECULAR FLEXIBLE FOR STRESS-FREE OPERATION FROM -55°C TO 125°C

☐ CC-7130-PRTC: MEETS AND EXCEEDS ALL "PARYLENE" CLASS PERFORMANCE
  - HYDROPHOBIC AND MOISTURE BARRIER PROTECTION FOR PWB AND ELECTRICAL CONTACTS

Figure 17: IPC-CC-830C certified SC7130-CC and CC7130-PRTC

SC7130-CC and CC7130-PRTC are new types of conformal coatings that have been tested to have the same performance as Parylene under the IPC-CC-830C standards and categorization. They have the same thin coating of 12.5 µm to 50 µm and higher insulation resistance even after extreme moisture exposure. The molecular structures have been engineered to be stress-free during temperature excursion and thermal shock. These new types of conformal coatings are also capable of blocking moisture and harmful gas ingress to prevent corrosion for longer term reliability. This new type of conformal coating is applied with traditional spray-dip-brush method for air-dry transparent coating that can be field applied and repaired.

APPENDIX 1: IPC-CC-830C Certification Test Report Summary[18] for SC7130-CC from AIT

SC7130-CC Per IPC-CC-830C Independent Lab Certification Results

Test	Procedure-Method	Requirements/Comments	Results
Coating Thickness (Spray and Dip Coating Method)	Thickness measurement	Thickness: Min. 12.5µm; Max. 50µm in meeting all requirements for "Parylene Classification" of performance. All other classes need heavier coating.	PASS
Visual inspection	On glass plate under white and UV light	Coating must have uniform appearance and consistency	PASS
Fluorescence	On glass plate under black (UV) light	Coating must fluoresce under UV black light (typical wavelength 365nm)	PASS
Fungus resistance	IPC-TM-650 section 2.6.1.1 on glass plate	Not attacked by biological growth	PASS
UL 94 test strip for flammability	**UL 94 HB**	**Must meet a minimum horizontal burning test**	**PASS; V-0 Self-Extinguishing**
Flexibility	IPC-TM-650 section 2.4.5.1 on tin panel	No evidence of cracking or crazing of the cured coating	PASS
Dielectric Withstanding Voltage	IPC-TM-650 sec. 2.5.7.1 on IPC-B-25A Test Board	No disruptive discharge, sparkover, or breakdown. @1500VAC, Max 10 uA leakage rate; **Pattern D insulation resistance $>10^{12}\Omega$**	PASS
Moisture and Insulation Resistance	**IPC-TM-650 section 2.6.3.4 on IPC-B-25A**	**Minimum 500MΩ for ER and 5GΩ for all other types after exposure to humidity within 1-2hours of exposure; Insulation resistance post moisture exposure: $>10^{11}\Omega$ = before exposure (No Degradation)**	**PASS, Meets Requirements for "Parylene Type"**
Thermal Shock	IPC-TM-650 section 2.6.7.1 on IPC-B-25A	Appearance and Dielectric Withstand Voltage after testing must meet the above-mentioned passing levels	PASS
Temperature and Humidity Aging	IPC-TM-650 sect. 2.6.11.1 on ‘‘Y Panel" test coupon	No evidence of softening, tack, cracking, loss of adhesion, or reversion	PASS
New Type of Conformal Coating from AI Technology, Inc.	➢ SC7130-CC is a new class of thin conformal coating with molecular structure of fluorinated polymer for hydrophobic and moisture barrier ➢ Designed for low cost spray-dip-brush coating methods to achieve 12.5-50µm thickness ➢ The strong and tight molecular stability is engineered for extreme conditions including salt-fog, salt-water, acid rain, and corrosive environments ➢ This Parylene replacement conformal coating has been proven to outperform all traditional conformal coating in more stringent Radio Technical Commission for Aeronautics (RTCA DO 160) applications		

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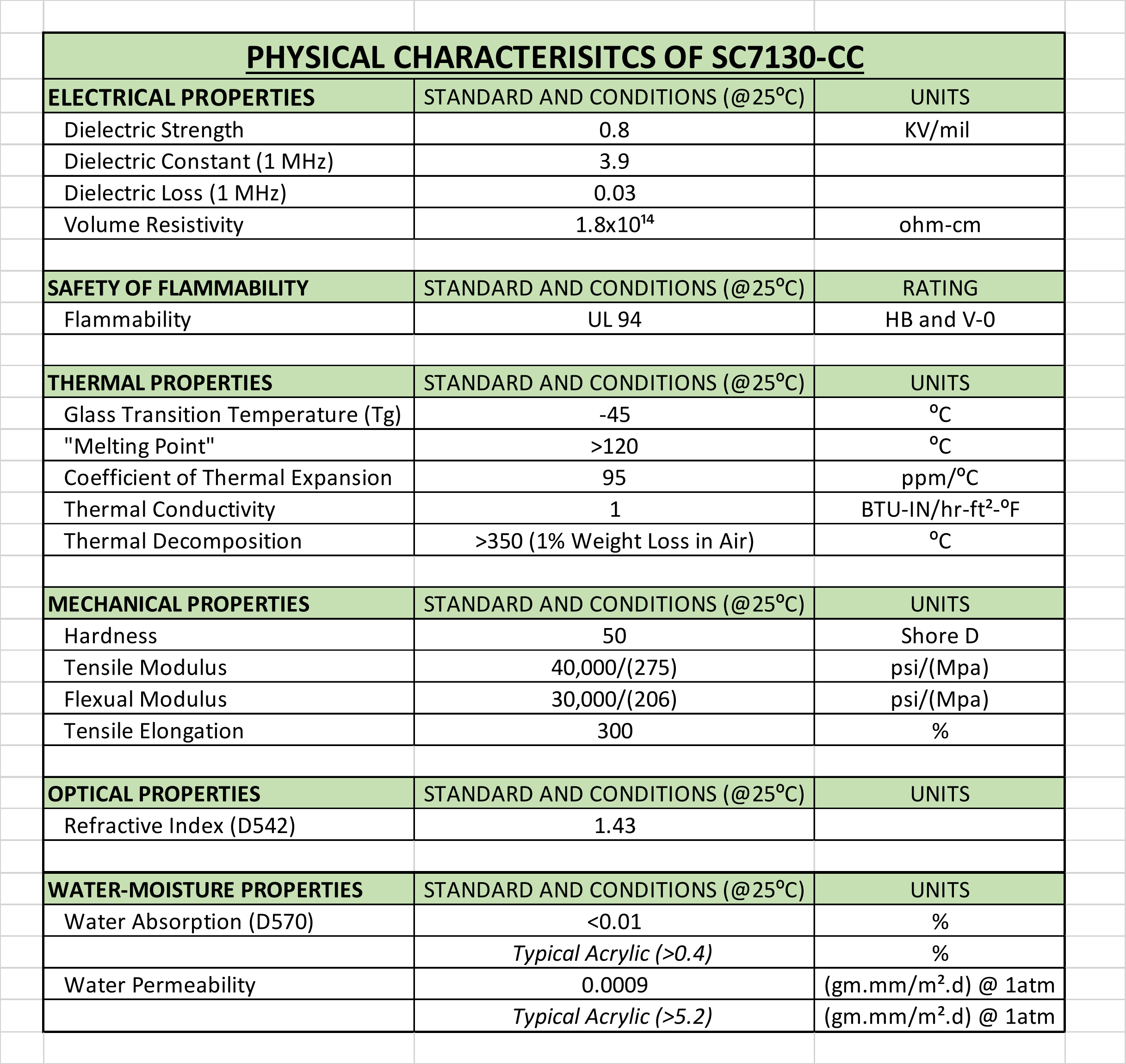
[18] NTS Test Report No. PR107890-00 Part 2 of 2

APPENDIX 2: Physical and Electrical Properties of SC7130-CC from AIT



PHYSICAL CHARACTERISITCS OF SC7130-CC		
ELECTRICAL PROPERTIES	STANDARD AND CONDITIONS (@25°C)	UNITS
Dielectric Strength	0.8	KV/mil
Dielectric Constant (1 MHz)	3.9	
Dielectric Loss (1 MHz)	0.03	
Volume Resistivity	$1.8x10^{14}$	ohm-cm
SAFETY OF FLAMMABILITY	STANDARD AND CONDITIONS (@25°C)	RATING
Flammability	UL 94	HB and V-0
THERMAL PROPERTIES	STANDARD AND CONDITIONS (@25°C)	UNITS
Glass Transition Temperature (Tg)	-45	°C
"Melting Point"	>120	°C
Coefficient of Thermal Expansion	95	ppm/°C
Thermal Conductivity	1	BTU-IN/hr-ft^2-°F
Thermal Decomposition	>350 (1% Weight Loss in Air)	°C
MECHANICAL PROPERTIES	STANDARD AND CONDITIONS (@25°C)	UNITS
Hardness	50	Shore D
Tensile Modulus	40,000/(275)	psi/(Mpa)
Flexual Modulus	30,000/(206)	psi/(Mpa)
Tensile Elongation	300	%
OPTICAL PROPERTIES	STANDARD AND CONDITIONS (@25°C)	UNITS
Refractive Index (D542)	1.43	
WATER-MOISTURE PROPERTIES	STANDARD AND CONDITIONS (@25°C)	UNITS
Water Absorption (D570)	<0.01	%
	Typical Acrylic (>0.4)	%
Water Permeability	0.0009	(gm.mm/m^2.d) @ 1atm
	Typical Acrylic (>5.2)	(gm.mm/m^2.d) @ 1atm

APPENDIX 3: IPC-CC-830C Certification Test Report Summary[19] for CC7130-PRTC from AIT

CC7130-PRTC Per IPC-CC-830C Independent Lab Certification Results			
Test	Procedure-Method	Requirements/Comments	Results
Coating Thickness (Spray and Dip Coating Method)	Thickness measurement	Thickness: Min. 12.5µm; Max. 50µm in meeting all requirements for "Parylene Classification" of performance. All other classes need heavier coating.	PASS
Visual inspection	On glass plate under white and UV light	Coating must have uniform appearance and consistency	PASS
Fluorescence	On glass plate under black (UV) light	Coating must fluoresce under UV black light (typical wavelength 365nm)	PASS
Fungus resistance	IPC-TM-650 section 2.6.1.1 on glass plate	Not attacked by biological growth	PASS
UL 94 test strip for flammability	**UL 94 HB**	**Must meet a minimum horizontal burning test**	**PASS**
Flexibility	IPC-TM-650 section 2.4.5.1 on tin panel	No evidence of cracking or crazing of the cured coating	PASS
Dielectric Withstanding Voltage	IPC-TM-650 sec. 2.5.7.1 on IPC-B-25A Test Board	No disruptive discharge, sparkover, or breakdown. 1500VAC, Max 10 uA leakage rate; **Pattern D insulation resistance >10^{12}Ω**	PASS
Moisture and Insulation Resistance	**IPC-TM-650 section 2.6.3.4 on IPC-B-25A**	**Minimum 500MΩ for ER and 5GΩ for all other types after exposure to humidity within 1-2hours of exposure;** **Insulation resistance post moisture exposure: >10^{11}Ω = before exposure (No Degradation)**	**PASS, Meets Requirements for "Parylene Type"**
Thermal Shock	IPC-TM-650 sec. 2.6.7.1 on IPC-B-25A	Appearance and Dielectric Withstand Voltage after testing must meet the above-mentioned passing levels	PASS
Temperature and Humidity Aging	IPC-TM-650 sec. 2.6.11.1 on ''Y Panel" test coupon	No evidence of softening, tack, cracking, loss of adhesion, or reversion	PASS
New Type of Conformal Coating from AI Technology, Inc.	➢ CC7130-PRTC is a new class of thin conformal coating with molecular structure of high density and crystallinity polymer for hydrophobicity and moisture barrier ➢ Designed for low cost spray-dip-brush coating methods to achieve 25-50µm thickness ➢ This Parylene replacement conformal coating is molecularly engineered for extreme conditions including salt-fog, salt-water, and moisture laden environments		

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[19] NTS Test Report No. PR107890-00 Part 1 of 2

APPENDIX 4: Physical and Electrical Properties of CC7130-PRTC from AIT

PHYSICAL CHARACTERISITCS OF CC7130-PRTC		
ELECTRICAL PROPERTIES	STANDARD AND CONDITIONS (@25°C)	UNITS
Dielectric Strength	0.7	KV/mil
Dielectric Constant (1 MHz)	2.9	
Dielectric Loss (1 MHz)	0.01	
Volume Resistivity	1.2x10^{14}	ohm-cm
SAFETY OF FLAMMABILITY	STANDARD AND CONDITIONS (@25°C)	RATING
Flammability	UL 94	HB and V-0
THERMAL PROPERTIES	STANDARD AND CONDITIONS (@25°C)	UNITS
Glass Transition Temperature (Tg)	-55	°C
"Melting Point"	>110	°C
Coefficient of Thermal Expansion	105	ppm/°C
Thermal Conductivity	0.6	BTU-IN/hr-ft^2-°F
Thermal Decomposition	>330 (1% Weight Loss in Air)	°C
MECHANICAL PROPERTIES	STANDARD AND CONDITIONS (@25°C)	UNITS
Hardness	65	Shore A
Tensile Modulus	20000/(138)	psi/(Mpa)
Flexual Modulus	15,000/(103)	psi/(Mpa)
Tensile Elongation	250	%
OPTICAL PROPERTIES	STANDARD AND CONDITIONS (@25°C)	UNITS
Refractive Index (D542)	1.5	
WATER-MOISTURE PROPERTIES	STANDARD AND CONDITIONS (@25°C)	UNITS
Water Absorption (D570)	<0.03	%
	Typical Acrylic (>0.4)	%
Water Permeability	<0.05	(gm.mm/m^2.d) @ 1atm
	Typical Acrylic (>5.2)	(gm.mm/m^2.d) @ 1atm