Moisture Diffusion Modelling of a Thin Film Acrylic Resin Based Conformal Coating on PCBA

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Abstract
High reliability process automation devices require serious protection from harsh environments which can be a combination of moisture, corrosive gases and liquids, salt sprays, large temperature variations, mechanical vibration and fungus. Conformal coatings of various resins provide such range of protection for electronics circuit boards. High levels of residual moisture accumulation in electronics can result in malfunction which can be a serious safety issue.

This paper discusses the analytical modelling of moisture diffusion and ingress rate through an Acrylic conformal coating, which is a good choice for addressing corrosive environments use, validated by FEA simulation. Diffusivity of materials is determined experimentally using IPC-TM-650 Method 2.6.28. In comparison, a silicone resin based coating is also considered in the study.

Mathematical equations have been developed for the calculation of the characteristic times of moisture diffusion in the Acrylic resin based conformal coating of different shapes and sizes to address topography issues. An argument is presented for use of adequate bake-out schedules for different situations which can be calculated based on the temperature dependency of the moisture diffusion coefficient of polymer materials.

The diffusion coefficient of the Acrylic conformal coating was experimentally determined using absorption data by weight gain experiment. Once the diffusivity coefficient is known, a theoretical fickian curve is plotted with the experimental data to confirm agreement of its behavior with the fickian curve. The 99% saturation approach is also used which helps to define the limit of fickian diffusion hence eliminate error caused by non-fickian absorption.

In comparison to thick films, thin film layers are thin enough that time to reach equilibrium concentration is relatively short and subsequent transport rates are governed by the diffusion behavior of the saturated film. Several moisture concentration curves were created based on the different compound, size and shape of the coating to understand the variation of moisture concentrations.

Finally, based on results and understanding of moisture ingress rate through Acrylic and silicone conformal coating material and considering deployment designed life of the product, proper selection of materials together in conjunction with proper bake-out cycles can be used or created specifically for the products to increase the reliability of the product in the field.

Introduction
The presence of moisture in electronic packages alters thermal stress through alteration of thermo-mechanical properties. For example; change of elastic modulus, shear strength and glass transition temperatures. Moisture also;

- Induces hygroscopic stress through differential swelling
- Reduces interfacial adhesion strength
- Induces ionic corrosion, leading to both open and short circuits
- Changes dielectric constant, leading to a reduction in circuit switching speeds and an increase in propagation delay times
- Changes the capacitance between the two electrodes separated by the PCB material
- Reduces glass transition temperature T_g
- Acts as an unwanted resistance when present between the two nodes of component and result in lowering the resistance

Conformal coating is applied to printed circuit boards (PCBs) to provide a dielectric layer on an electronic board. This layer functions as a membrane between the board and the environment. With this coating in place, the PCB can withstand more moisture by increasing the surface resistance or surface insulation resistance (SIR). With a higher SIR board, the risk of problems such as cross talk, electrical leakage, intermittent signal losses, and shorting is reduced. This reduction in moisture will also help to reduce metallic growth called dendrites and corrosion or oxidation. Conformal coating will also serve to shield a PCB from dust, dirt and pollutants that can carry moisture and may be acidic or alkaline.

The ideal conformal coating will have performance requirements that include good electrical characteristics, low moisture permeability, good chemical resistance and mechanical integrity. It must adhere to the printed circuit board and mix of component surfaces. There are several choices of both conventional and new materials available for use as conformal coatings. Understanding end use application is vital in making the appropriate selection. For example, an acrylic coating might not be the ideal choice for an automotive application, due to the high temperatures involved and exposure to moisture or petroleum residues. A better choice would be a silicone coating, which has a usable operating range of -55°C to +200°C and offers resistance to high humidity environments.

Commonly Used Conformal Coating Materials
A few common industry resin types are discussed below.

Silicone
Silicone conformal coatings are most widely used in high temperature environments due to their innate ability to withstand prolonged exposure to higher temperatures compared to most other conformal coating chemistries. This attribute has made them the primary choice for under hood automotive applications. They are also capable of being applied in thicker films making them useful as a vibration dampening (isolation tool) if the coated assembly is to be placed in a high vibration environment. Rework of silicone coated assemblies can sometimes be difficult due to their chemical resistance and the fact that, unlike Acrylics and Polyurethanes, they do not vaporize with the application of heat.

Polyurethane
Polyurethane formulations provide excellent humidity resistance and far greater chemical resistance than Acrylic coatings. They require very lengthy cure cycles to achieve full or optimum cure. Removal of polyurethane coatings can be difficult due to their very high resistance to solvents.

Epoxy
Epoxy coatings are very hard, usually opaque, and good at resisting the effects of moisture and solvents. Epoxy is usually available as a two part thermosetting mixture and shrinks during curing leaving a hard, difficult to repair film. It possesses excellent chemical and abrasion resistance but can cause stress on components during thermal extremes. Epoxy is quite easy to apply but nearly impossible to remove without damaging the components.

Acrylic
Acrylic conformal coatings are perhaps the most popular of all conformal coating materials due to their ease of application, removal and forgiving nature. Acrylics dry rapidly, reaching optimum physical properties in minutes, are fungus resistant and provide long pot life. Additionally, acrylics give off little or no 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 transitiontemperatures. The material also has a continuous operation range of -65°C to+125°C.Moisture resistance of this type of coating is good but resistance to organic solvents is relatively poor.

Poly-para-xylylene
This is a unique coating process. Di-p-xylylene is pyrolyzed at a temperature approximating 650°C in a high vacuum environment causing the monomer to polymerize on all PCB and component surfaces present in the high vacuum environment giving a very even pinhole free coating. A unique difference with the Poly-para-xylylene process is that it also coats the underside of low profile components due to the thin application of the coating.

Table 1 summarizes the properties and comments about each of these conformal coatings.

Table 1: Materials Types and Characteristics

Type	Material Cost	Ease of Application	Ease of Repairs	Temperature Range	Solvent Resistance	Electrical Resistance	Abrasion Resistance	Moisture Resistance
Acrylic	Low Cost	Multiple Methods	Easy to Touch Up	Good Range	Poor	Good	Good	High
Silicone	Higher Costs	Contaminates Other Materials	Difficult	Excellent	Good	Excellent	Good	Excellent
Urethane	Low Cost	Multiple Methods	Very Difficult	Good Range	Excellent	Excellent	Excellent	Acceptable
PTFE	Higher Costs	Specialized Equipment	Very Difficult	Excellent	Excellent	Excellent	Excellent	Acceptable
Poly-para-xylylene	Higher Costs	Specialized Equipment	Very Difficult	Excellent	Excellent	Excellent	Excellent	Excellent

Coating Acceptance Criteria

IPC has available standards that are used widely in the industry for testing and qualification of coatings. For example;

1. IPC-HDBK-830 guidelines for design, selection and application of conformal coatings
2. IPC-TM-650 Method 2.6.3.1 to measure insulation resistance
3. IPC-TM-650 Method 2.5.7 to measure dielectric withstanding voltage
4. IPC-TM-650 Method 2.6.7.1 to measure thermal shock
5. IPC-TM-650 method 2.4.26 to measure adhesion

As per IPC-A-610F coating thickness for each resin type is defined which is widely used in the industry as a reliable guideline. Figure 1 is the table from IPC-A-610F;

Type AR	Acrylic Resin	0.03-0.13 mm [0.00118-0.00512 in]
Type ER	Epoxy Resin	0.03-0.13 mm [0.00118-0.00512 in]
Type UR	Urethane Resin	0.03-0.13 mm [0.00118-0.00512 in]
Type SR	Silicone Resin	0.05-0.21 mm [0.00197-0.00827 in]
Type XY	Paraxylylene Resin	0.01-0.05 mm [0.00039-0.00197 in]

Figure 1: Table 10-1 Coating Thickness form IPC-A-610F

Harsh Environment Applications

Process instruments that are used particularly in harsh environments like oil rigs, process plants that are processing gases like inorganic chlorine compounds (Cl_2), active sulphur compounds (H_2S), sulfur oxides (SOx), Nitrogen oxides (NO_x), hydrogen fluoride (HF), ammonia and derivatives (NH_3) and petrochemical species (O_3), are required to have electronics protected to last longer and work reliably under such conditions as described in the standard ANSI/ISA-S71.04 (1985): *Environmental Conditions for Process Measurement and Control Systems: Airborne Contaminants*. The purpose of this standard is to classify airborne contaminants that may affect process measurement and control systems. It provides users and manufacturers of instruments with a means of specifying the type and concentration of airborne contaminants to which a specified instrument may be exposed. Hence providing a standard to achieve thorough design and process materials. Among four severity levels, G3 classification is for application environments where gas contaminants are considered harsh with a capability of forming a greater than 2000 angstroms film on exposed copper after one-month exposure. Figure 2 shows different classifications from the standard.

	Contaminant	Concentration	Reference Class/ Severity	Reference Table No.
Liquids:	Trichloroethylene	<5 μg/kg	LA2	1
	Oils	<100 μg/kg	LB3	1
	Sea salt mist	Within 0.5 km inland	LC2	1
Solids:	Particle size	Concentration level		
	>1 mm	<1000 μg/m^3	SA1	2
	100 to 1000 μm	<3000 μg/m^3	SB2	2
	1 to 100 μm	<350 μg/m^3	SC3	2
	<1 μm	<350 μg/m^3	SD3	2
Gases:	Harsh: >2000 angstroms film formation on exposed copper coupon after one month exposure		G3	3

Figure 2: Different Classifications for Corrosive Medium

There is a broad distribution of contaminant concentrations and reactivity levels existing within industries using process measurement and control equipment. Some environments are severely corrosive, while others are mild. The purpose of the contaminant classes is to define environments on the basis of corrosion rate of oxygen-free high conductivity copper, which is prepared and tested.

- Severity level G1 - Mild — an environment sufficiently well-controlled such that corrosion is not a factor in determining equipment reliability.
- Severity level G2 - Moderate — an environment in which the effects of corrosion are measurable and may be a factor in determining equipment reliability.
- Severity level G3 - Harsh — an environment in which there is a high probability that corrosive attack will occur. These harsh levels should prompt further evaluation resulting in environmental controls or specially designed and packaged equipment.
- Severity level GX - Severe — an environment in which only specially designed and packaged equipment would be expected to survive. Specifications for equipment in this class are a matter of negotiation between user and supplier.

Each site may have different combinations and concentration levels of corrosive gaseous contaminants. Performance degradation can occur rapidly or over many years, depending on the particular concentration levels and combinations present at a site. The following paragraphs describe how various pollutants contribute to equipment performance degradation.

Theoretical Moisture Diffusion

Fick's second law, Equation (1), is used in non-steady or continually changing state diffusion which is when the concentration within the diffusion volume changes with respect to time.

$$\frac{1}{D}\frac{\partial C}{\partial t} = \frac{\partial^2 C}{\partial x^2} + \frac{\partial^2 C}{\partial y^2} + \frac{\partial^2 C}{\partial z^2} \qquad (1)$$

Where;
C = concentration of diffusing substance (g/cm^3)
D = diffusion coefficient (cm^2/sec)
x,y,z = dimensions in x, y and z direction (cm)

Polymeric packaging materials transport moisture primarily by diffusion, although secondary effects such as surface tension and pressure driven flows may also contribute. Moisture transport strictly by diffusion is modeled using the standard transient diffusion as per Fick's second law. Wong, Koh, Lee and Rajoo (2002) [1] showed that the Crank's equation (Mathematics of Diffusion, 1956), can be modified into Equation (2) to calculate the diffusion coefficient for isotropic materials.

$$\frac{M_t}{M_\infty} = 1 - \frac{8}{\pi^2} \sum_{m=0}^{\infty} \frac{1}{(2m+1)^2} \exp\left[\frac{-D(2m+1)^2 \pi^2 t}{h^2}\right] \tag{2}$$

Where;
h = total sheet thickness (mm)
M_t = total mass of the diffusing substance absorbed at time t
M_∞ = Equilibrium mass of the absorbed substance
D = diffusion coefficient (mm^2/hour)

Since the Equation (2) assumes that there is no diffusion from the edges of the specimen or it is only true for a large aspect ratio, Equation (3) is the correction factor needed to compensate diffusion in the z-direction, as prescribed by Wong, Koh, Lee and Rajoo (2002)[1]

$$D_z = C_f \, x \, D_{1-D} \tag{3}$$

For a square specimen,

$$C_f = \frac{1}{1 + \left(\frac{2z}{x}\right)^2} \tag{4}$$

Where;
C_f = correction factor
Z = thickness of specimen (mm)
X = length/width ratio of the specimen

Zhou, Coffin and Arvelo (2006) [2] suggested another correction factor, as shown in Equation (5).

$$D_c = D\left(1 + \frac{h}{l} + \frac{h}{w}\right) \tag{5}$$

Where;
D = diffusion coefficient neglecting edge effect (mm^2/hour)
D_c = diffusion coefficient including edge effect (mm^2/hour)
h = height or thickness of the specimen (mm)
l = length of the specimen (mm)
w = width of the specimen (mm)

Using Crank's equation (Mathematics of Diffusion, 1956), shown in Equation (6);

$$\frac{C(x,t)}{C_\infty} = 1 - \frac{4}{\pi} \sum_{n=0}^{\infty} \frac{(-1)^n}{2n+1} \exp\frac{\left[-D(2n+1)^2 n^2 t\right]}{4l^2} \frac{\cos(2n+1)\pi x}{2l} \tag{6}$$

Where;
l = half thickness of sheet (mm)

D = Diffusion coefficient (mm^2/hour)
t = time (hour)
C = concentration of diffusing substance in time t (g/mm^3)
$C\infty$ = Saturated concentration of the absorbed substance (g/mm^3)

In the initial stages of absorption where $M_t/M_\infty < 0.5$ and assuming a constant diffusion coefficient, D, the above equation can be approximated to Equation (7) as shown by Wong, Koh, Lee and Rajoo (2002) [1].

$$\frac{M_t}{M_\infty} = \frac{4}{h}\sqrt{\frac{Dt}{\pi}} \tag{7}$$

If absorption data is plotted with M_t/M_∞ as a function of $(t/h^2)^{1/2}$ and exhibits linear behaviour for $M_t/M_\infty < 0.5$, the diffusion coefficient can be determined by re-arranging Equation (7) to Equation (8);

$$D = \frac{\pi}{16}\left[\frac{M_t/M_\infty}{\sqrt{t}/h}\right]^2 \tag{8}$$

The diffusivity, D, can now be experimentally determined using absorption data (M_t/M_∞) by weight gain experiment as prescribed in ASTM D570 and IPC-TM-650 method 2.6.28.

Table 2: Water Absorption Properties from Experiment

Water Absorption, % (168 hours @ 25°C)	Acrylic Resin	Silicone Resin
	0.3	0.35

Inserting the values of M_t/M_∞ in Equation (8) for AR (Acrylic Resin) and SR (Silicone Resin) based conformal coatings, we get the data as shown in Table 3;

Table 3: Diffusion Coefficient Values of AR and SR Resin Based Conformal Coatings

	Acrylic Resin	Silicone Resin
Average Thickness (mm)	0.03	0.05
Diffusion Coefficient (mm^2/hours)	3.60E-06	8.94E-06

For FR-4 PCB, values are taken from Pecht, M.G. (1999) [3], as shown in the Table 4 below;

Table 4: Diffusion Coefficient Values of FR-4 PCB

	FR-4
Average Thickness (mm)	1.65
Diffusion Coefficient (mm^2/hours)	8.15E-03

Once the diffusion coefficient is known, the theoretical Fickian curve can be plotted with the experimental data to see if the absorption is Fickian or not. This can be done by using the value of "D" calculated from weight gain experiments and plotting the graph with different time values. Equation (9) can be used;

$$\frac{M_t}{M_\infty} = 1 - \exp\left[-7.3\left(\frac{Dt}{h^2}\right)^{0.75}\right] \tag{9}$$

Comparison of data between theoretical and experimental data for both resins of conformal coating are shown below in Figure 3

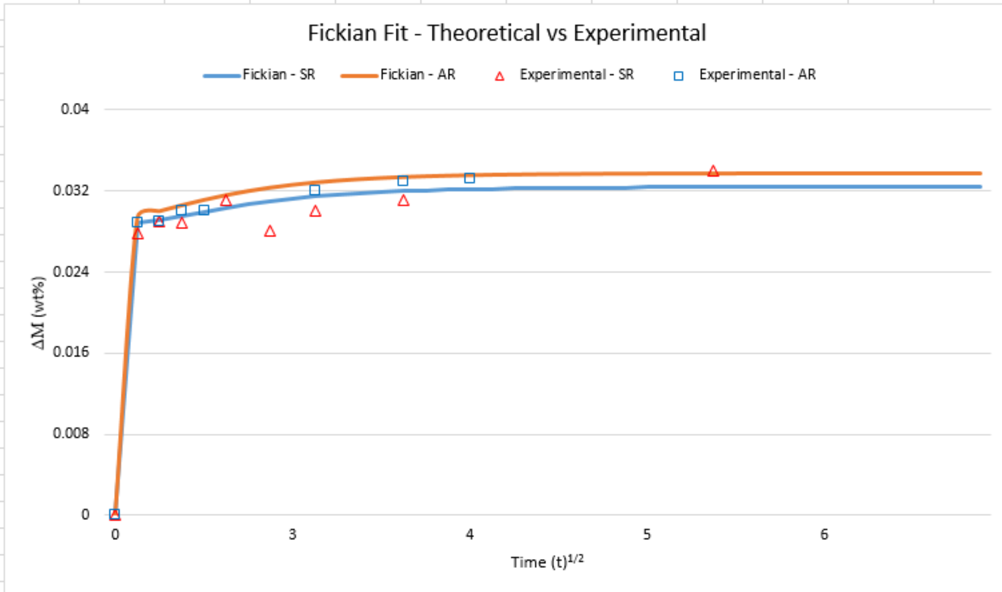

Figure 3: Fickian fit – Theoretical vs Experimental

For very prolonged times the curve becomes non-fickian, therefore, the diffusion coefficient is calculated by considering only the linear part of the curve. For materials showing non-fickian behavior, Wong, Koh, Lee and Rajoo (2002) [1] suggested to use the following Equation (10);

$$t_{99\%} = \frac{0.45\,h^2}{D} \qquad (10)$$

Where;
$t_{99\%}$ = time to approach 99% saturation (hours)
h = height or the thickness of the specimen (mm)
D = diffusion coefficient (mm^2/hour)

The 99% saturation approach helps to define the limit of Fickian diffusion hence eliminate error caused by non-fickian sorption. Using equation 10, moisture ingress rate can be calculated. The resultant data is shown in the Table 5 below;

Table 5: Ingress Rate, $t_{99\%}$

	Acrylic Resin	Silicone Resin	FR-4
Average Thickness (mm)	0.03	0.05	1.65
$t_{99\%}$ (hours)	112.49	125.72	150.40
$t_{99\%}$ (days)	4.68	5.23	6.26

From the mathematical models discussed above, it takes approximately 112 hours for the Acrylic resin based conformal coating to fully saturate with water whereas 125 hours for Silicone resin based conformal coating. This correlates to the information we already know that Silicone is better to resist moisture absorption compared to Acrylic.

To validate the data, FEA simulation study is presented below.

FEA Simulation of Moisture Diffusion

Since the Fick's moisture diffusion equation follows the same governing differential equation as the diffusion of heat (Fourier,1822), with a change of the dependent variable, temperature, with moisture concentration and the thermal diffusivity with moisture diffusivity, commercially available heat transfer simulation software can be used to solve transient moisture diffusion problems. However, a unique problem arises in the diffusion of moisture. Since 'D' is constant for a particular material, for bi-material analysis, interfacial concentration discontinuity cannot be analyzed. An interfacial discontinuity results where two materials having different saturated concentrations are joined. To use heat transfer simulation software for moisture diffusion simulation, manipulation in defining material properties is required. The substitutions are shown in Table 6.

Table 6: Material Properties Substitution for Moisture Study

Feature	Heat Transfer	Moisture Diffusion
Field Variables	Temperature, T	Moisture Concentration, C
Density	ρ, density (kg/m^3)	1
Conductivity	K, Conductivity (W/m.ºK)	D * C_{sat} (kg/sec.m)
Specific Heat	c (J/kg ºK)	C_{sat} (kg/m^3)
Thermal Expansion Coefficient	α	β .C_{sat}

Coefficient of Moisture Expansion (CME)is a measure of the change in the material strain with change in the moisture concentration. It is similar as 'α', the coefficient of thermal expansion (CTE). Thus as thermal stresses are generated due to CTE mismatch among materials, likewise hygro-mechanical stresses are induced due to CME mismatch among different material components of the package.

Material Properties Values for FEA Simulation

The final material properties for moisture diffusion study is shown below in the Table 7

Table 7: Material Properties Data for Moisture Study

	Acrylic		Silicone		FR-4	
	Heat Transfer	Moisture Diffusion	Heat Transfer	Moisture Diffusion	Heat Transfer	Moisture Diffusion
Mass Density (Kg/m^3)	920	1	1200	1	1850	1
Thermal Expansion Coefficient (ppm/K)	1.3E-04	1.4245 (β*C_{sat})	5.2E-05	1.1375 (β*C_{sat})	60	0.0102 (β*C_{sat})
Thermal Conductivity (W/m*K)	0.2	1.6898E-16 (D*C_{sat})	0.158	8.375E-16 (D*C_{sat})	0.3	2.307E-12 (D*C_{sat})
Specific Heat (J/Kg*k)	1470	0.77 (C_{sat})	1507	0.65 (C_{sat})	880	1.02 (C_{sat})

Model and Boundary Conditions for FEA Simulation

Simple models were made, dimensionally same, for each coating resin type and FR-4 PCB as shown below in the Figures 4-5, where Figure 4 is representing both Acrylic and Silicone Resin and Figure 5 is representing assembly model of SR resin and FR-4.

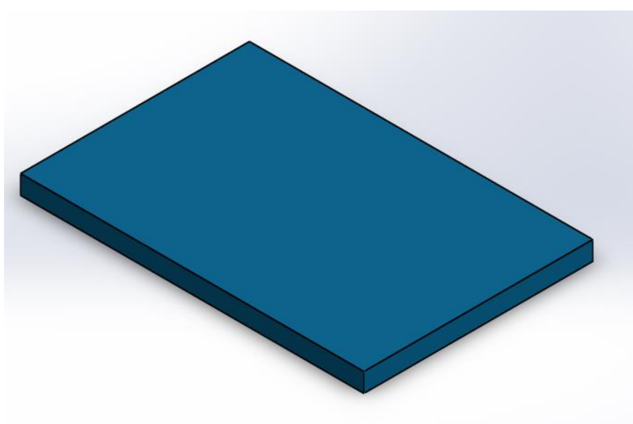

Figure 4: Model for Acrylic and Silicone Coating Simulation

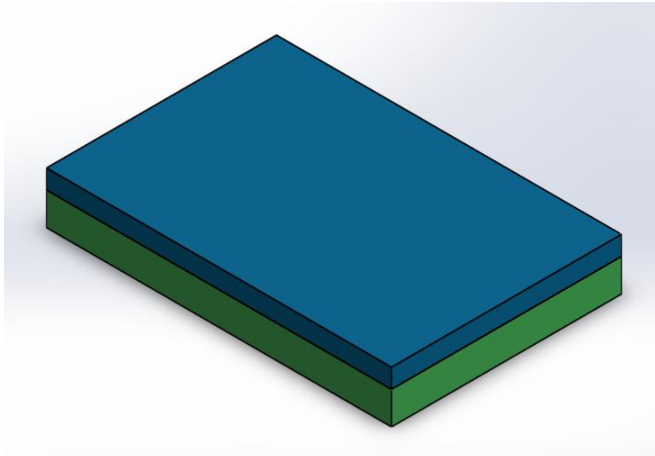

Figure 5: Model for Coating and FR-4 Assembly Simulation

As shown in Figure 6, Face 1 is the exposing face of the coating where moisture is applied and therefore concentration on Face 1 is set to 1, meaning completely wet. The rest of the faces; 2,3,4,5&6 are defined as completely dry faces and concentration set to 0.

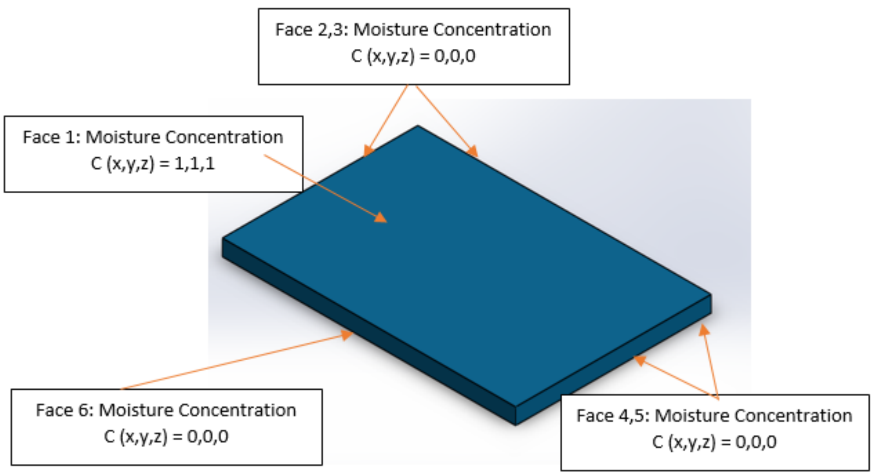

Figure 6: Boundary Conditions for FEA Modelling

Where;
C = 0 for complete dryness
C = 1 for saturated wetness

Meshed models are shown below, where Figure 7 is representing meshed model for both AR and SR resin coatings and Figure 8 is representing meshed model of conformal coating and FR-4 substrate assembly for bi-material interconnection study.

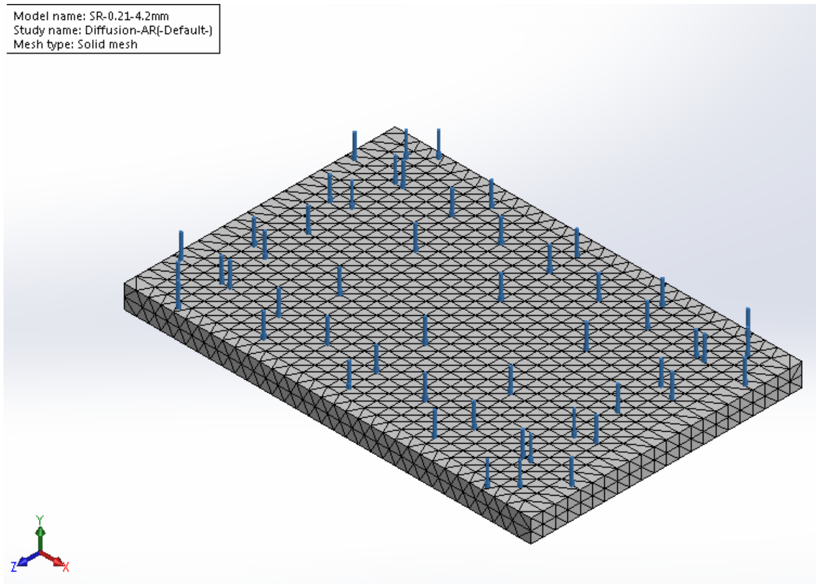

Figure 7: Meshed Model of Coating Model

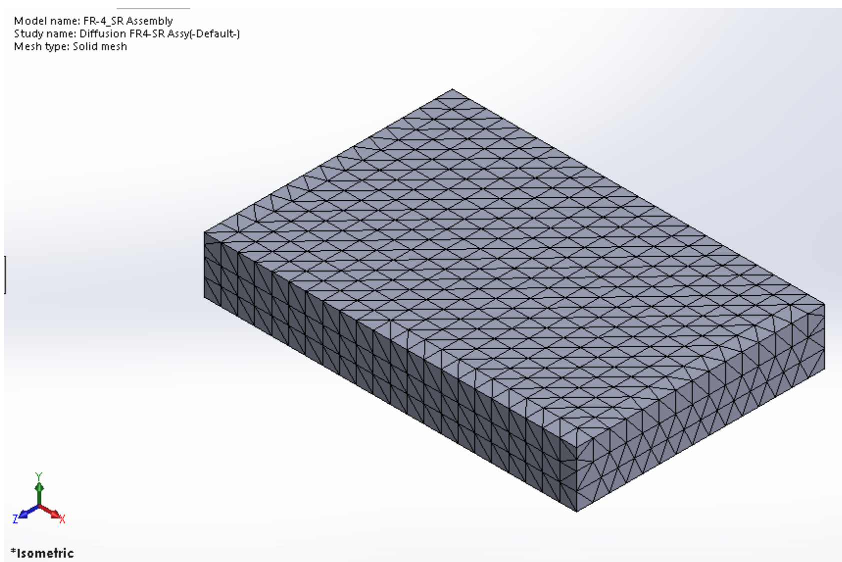

Figure 8: Meshed Model of Coating and FR-4 Substrate Assembly Model

Results

The following are the results of the moisture diffusion simulation of conformal coatings as shown in Figures 9 to 10.

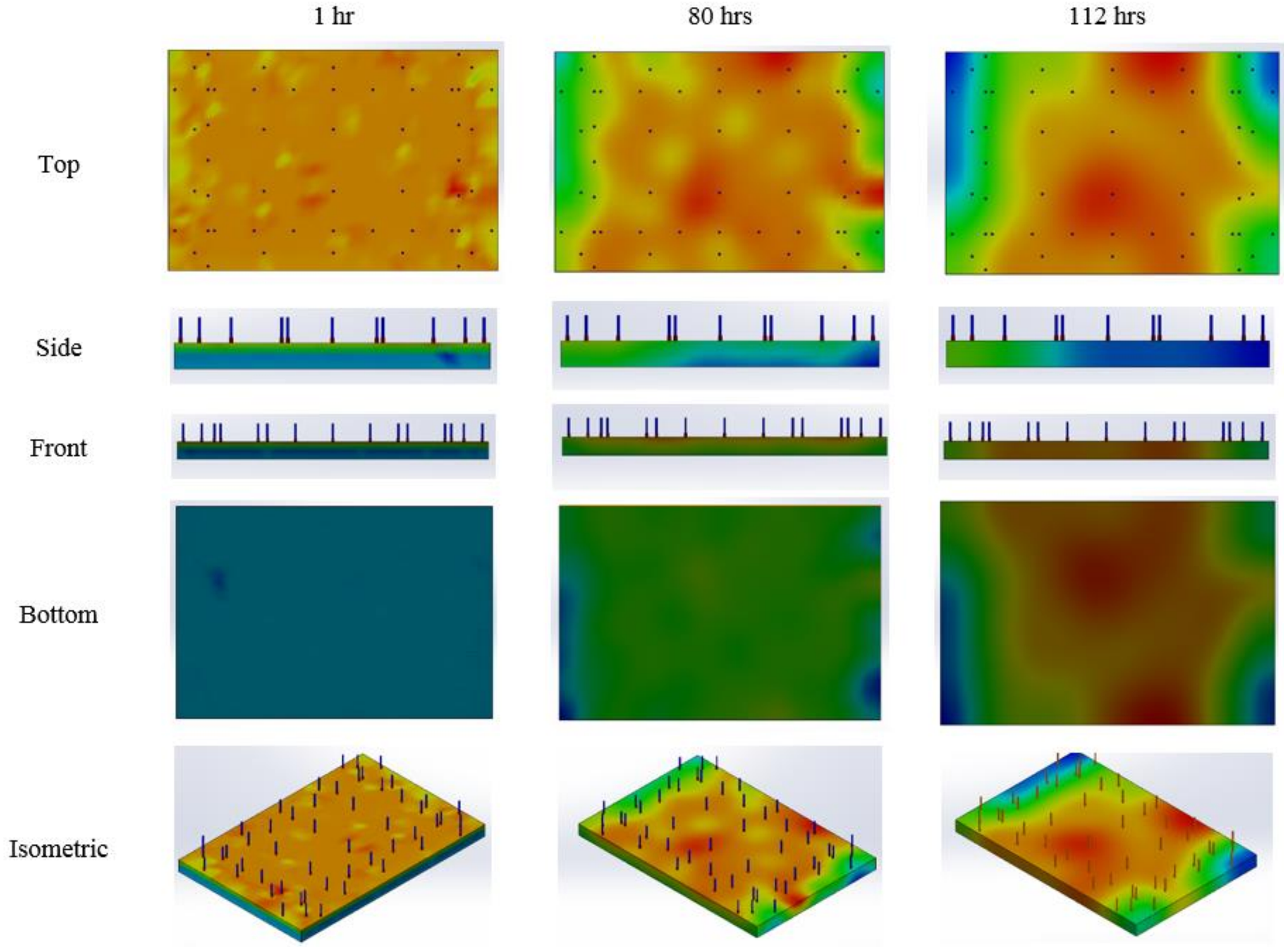

Figure 9: Moisture Diffusion through Acrylic Resin Based Conformal Coating Over Time

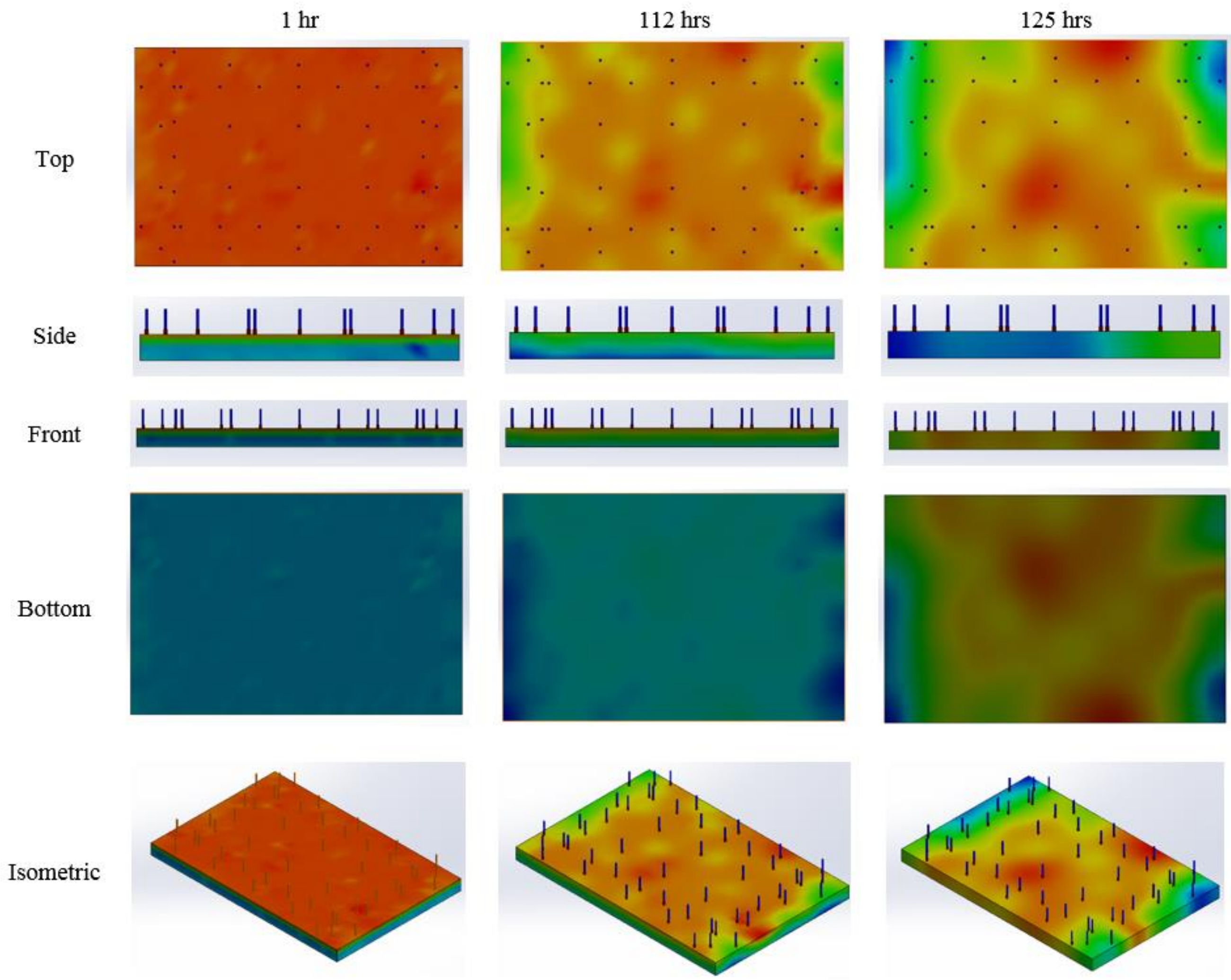

Figure 10: Moisture Diffusion through Silicone Resin Based Conformal Coating Over Time

For analyzing a biomaterial interface, an assembly model was created and simulated using the diffusion properties of both materials. Figure 11 represents the boundary conditions for the bi-material model for conformal coating and FR-4 substrate assembly, results of such modelling are presented in Figure 12.

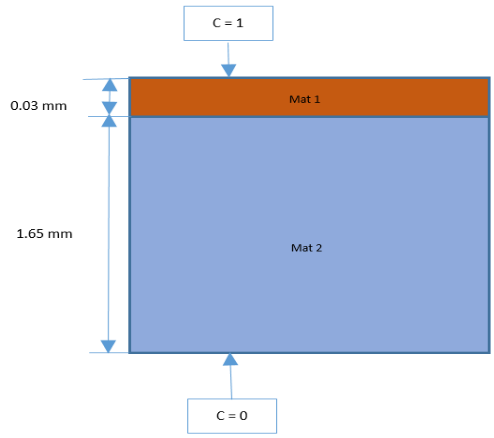

Figure 11: Boundary Conditions for Bi-material Model

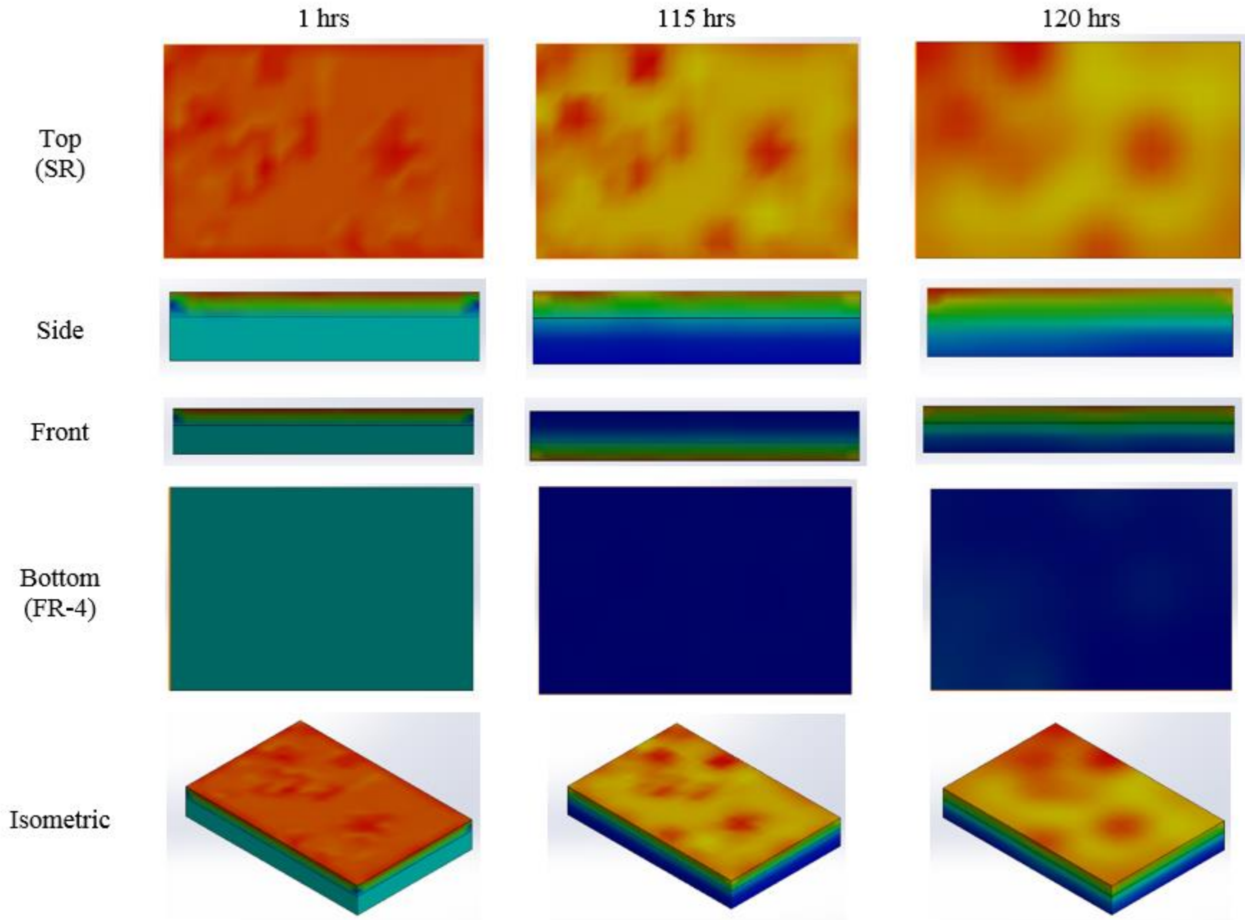

Figure 12: Moisture Diffusion through Acrylic Resin Based Conformal Coating and FR-4 Substrate Assembly Over Time

From the simulation results it is observed that both materials separately are in agreement with the ingress rate as calculated and shown in Table 5. The interface of the coating and PCB is where the diffusion slows down and moisture concentration increases before diffusion starts again through the PCB.

The moisture uptake results are shown in Figure 13 which correlates to the theoretical curves.

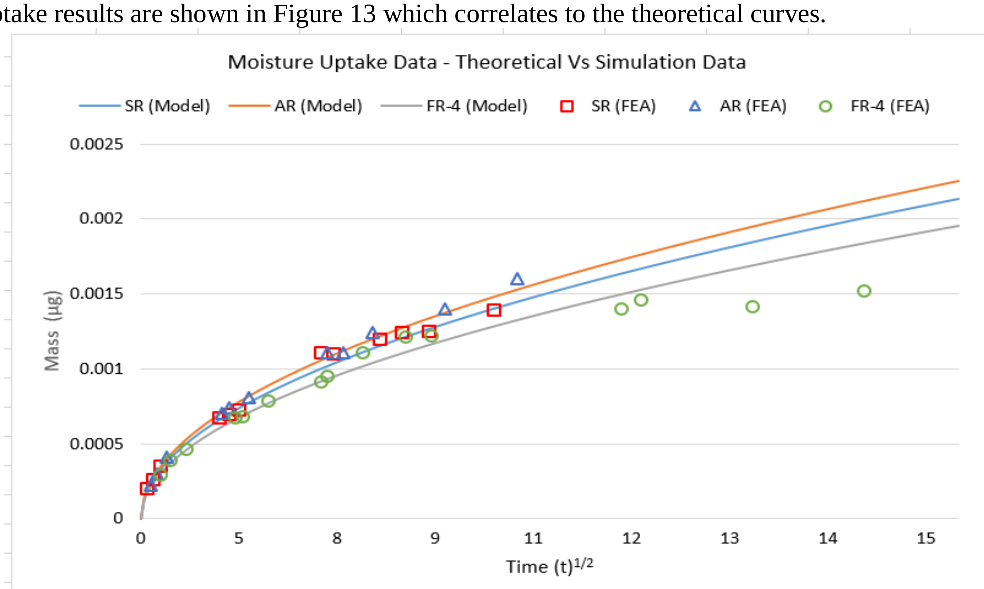

Figure 13: Moisture Uptake Data Correlation Between Theoretical and Simulation Values

Conclusions

The analysis performed in this work provides an insight on the order and distribution of moisture in the conformal coatings of two types, acrylic and silicone. Experimental methods to determine the diffusivity of materials and verifying the behavior used fickian curves. Once the diffusion coefficient is determined and verified, FEA simulation can be easily used to do a wide range of studies much faster with accuracy to learn more about diffusions affecting assemblies where more components of different materials are involved.

The physical dimensions of objects are important as it affects the diffusivity, especially in lateral directions, which means the thicker the coating the slower the diffusion would be. But the range presented by IPC, shown in the Figure 1, is very small and it virtually doesn't make any difference in the results. A few prominent points observed in the study are below;

- Comparison of moisture diffusion rates between a theoretical model and an analytical simulation are in reasonable agreement
- Coefficient of diffusion of materials depends on moisture concentration in the order of magnitudes of thousands of hours as it increases. This information is helpful when specifying a bake out cycle for desorption.
- Numerical computations, as shown above, allow for calculation of the distribution of moisture concentration, C(t), across the thickness of a material at different times of exposure to humid environments.
- Acrylic resin based coating absorbed more aggregate moisture than silicone resin based coating
- The diffusion rate of the AR coating is 2.5 times faster than the SR coating. It is attributed to the different chemistry in each conformal coating type
- The FEA model shows that moisture will initially reach the interface of coating and PCB using the Acrylic conformal coating as compared to the silicone conformal coating. However, due to the higher saturation concentration of acrylic chemistry, more moisture will arrive at the interface if exposed to the moist environment for longer durations.

References

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Moisture Diffusion Modelling Through a Thin Film Acrylic Resin Based Conformal Coating On PCBA

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Agenda

- Introduction
- Protection from Moisture
- IPC standards and ANSI/ISA-S71.04
- Moisture Diffusion Model
- Determining Diffusion Coefficient – Theoretical vs Experimental
- FEA Simulation of Moisture Diffusion
- Conclusion

Introduction

The presence of moisture affects thermo-mechanical properties, like;

- Change of Elastic Modulus & Shear Strength
- Induces hygroscopic stress through differential swelling
- Reduces interfacial adhesion strength
- Induces ionic corrosion, leading to both open and short circuits
- Changes dielectric constant, leading to a reduction in circuit switching speeds and an increase in propagation delay times
- Changes the capacitance between the two electrodes separated by the PCB material
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Protection from Moisture

- Conformal coating is applied to printed circuit boards (PCBs) to provide a dielectric layer on an electronic board.
- This layer functions as a membrane between the board and the environment. With this coating in place, the PCB can withstand more moisture by increasing the surface resistance or surface insulation resistance (SIR).
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- This reduction in moisture will also help to reduce metallic growth called dendrites and corrosion or oxidation.
- Conformal coating will also serve to shield a PCB from dust, dirt and pollutants that can carry moisture and may be acidic or alkaline.

Coating Material Types and Characteristics

Type	Material Cost	Ease of Application	Ease of Repairs	Temperature Range	Solvent Resistance	Electrical Resistance	Abrasion Resistance	Moisture Resistance
Acrylic	Low Cost	Multiple Methods	Easy to Touch Up	Good Range	Poor	Good	Good	High
Silicone	Higher Costs	Contaminates Other Materials	Difficult	Excellent	Good	Excellent	Good	Excellent
Urethane	Low Cost	Multiple Methods	Very Difficult	Good Range	Excellent	Excellent	Excellent	Acceptable
PTFE	Higher Costs	Specialized Equipment	Very Difficult	Excellent	Excellent	Excellent	Excellent	Acceptable
Poly-para-xylylene	Higher Costs	Specialized Equipment	Very Difficult	Excellent	Excellent	Excellent	Excellent	Excellent

Harsh Environment Standard and Classification of Corrosive Medium

	Contaminant	Concentration	Reference Class/ Severity	Reference Table No.
Liquids:	Trichloroethylene	<5 µg/kg	LA2	1
	Oils	<100 µg/kg	LB3	1
	Sea salt mist	Within 0.5 km inland	LC2	1
Solids:	Particle size	Concentration level		
	>1 mm	<1000 µg/m^3	SA1	2
	100 to 1000 µm	<3000 µg/m^3	SB2	2
	1 to 100 µm	<350 µg/m^3	SC3	2
	<1 µm	<350 µg/m^3	SD3	2
Gases:	Harsh: >2000 angstroms film formation on exposed copper coupon after one month exposure		G3	3

ANSI/ISA-S71.04 (1985): *Environmental Conditions for Process Measurement and Control Systems: Airborne Contaminants*

- Process instruments that are used particularly in harsh environments like oil rigs, process plants that are processing gases like inorganic chlorine compounds (Cl_2), active sulphur compounds (H_2S), sulfur oxides (SOx), nitrogen oxides (NO_x), hydrogen fluoride (HF), ammonia and derivatives (NH_3) and petrochemical species (O_3), requires to have electronics protected to last longer and work reliably under such conditions.

IPC Standards for Thickness and Testing

- IPC-HDBK-830 guidelines for design, selection and application of conformal coatings
- IPC-TM-650 Method 2.6.3.1 to measure insulation resistance
- IPC-TM-650 Method 2.5.7 to measure dielectric withstanding voltage
- IPC-TM-650 Method 2.6.7.1 to measure thermal shock
- IPC-TM-650 method 2.4.26 to measure adhesion
- IPC-A-610F

Type AR	Acrylic Resin	0.03-0.13 mm [0.00118-0.00512 in]
Type ER	Epoxy Resin	0.03-0.13 mm [0.00118-0.00512 in]
Type UR	Urethane Resin	0.03-0.13 mm [0.00118-0.00512 in]
Type SR	Silicone Resin	0.05-0.21 mm [0.00197-0.00827 in]
Type XY	Paraxylylene Resin	0.01-0.05 mm [0.00039-0.00197 in]

Moisture Diffusion Model

$$\frac{1}{D}\frac{\partial C}{\partial t} = \frac{\partial^2 C}{\partial x^2} + \frac{\partial^2 C}{\partial y^2} + \frac{\partial^2 C}{\partial z^2}$$

Where;

C = concentration of diffusing substance (g/cm^3)

D = diffusion coefficient (cm^2/sec)

x,y,z = dimensions in x, y and z direction (cm)

$$D = \frac{\pi}{16}\left[\frac{M_t / M_\infty}{\sqrt{t} / h}\right]^2$$

Where;

h = total sheet thickness (mm)

M_t = total mass of the diffusing substance absorbed at time t

M_∞ = Equilibrium mass of the absorbed substance

D = diffusion coefficient (mm2/hour)

Determining Diffusion Coefficient of Materials

Using weight gain data as experimentally determined using IPC-TM-650 method 2.6.28 and following equation

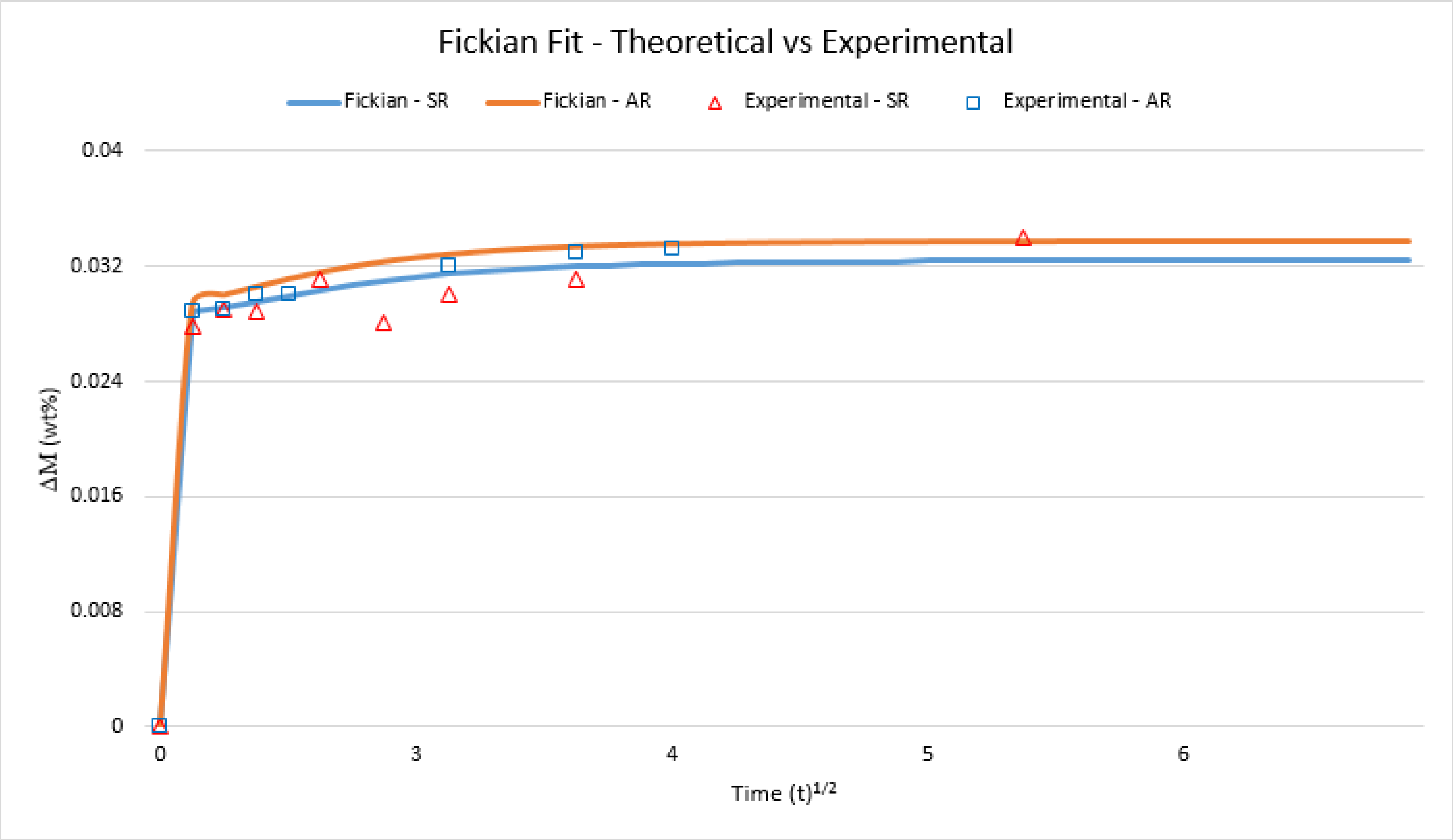
	Acrylic Resin	Silicone Resin
Water Absorption, % (168 hours @ 25°C)	0.3	0.35

	Acrylic Resin	Silicone Resin
Average Thickness (mm)	0.03	0.05
Diffusion Coefficient (mm^2/hours)	3.60E-06	8.94E-06

	FR-4
Average Thickness (mm)	1.65
Diffusion Coefficient (mm^2/hours)	8.15E-03

Fickian Fit – Theoretical vs Experimental

$$\frac{M_t}{M_\infty} = 1 - \exp\left[-7.3\left(\frac{Dt}{h^2}\right)^{0.75}\right]$$



99% Saturation Approach, $t_{99\%}$

$$t_{99\%} = \frac{0.45\,h^2}{D}$$

Where;

$t_{99\%}$ = time to approach 99% saturation (hours)

h = height or the thickness of the specimen (mm)

D = diffusion coefficient (mm^2/hour)

Wong, Koh, Lee and Rajoo (2002) [1]

	Acrylic Resin	Silicone Resin	FR-4
Average Thickness (mm)	0.03	0.05	1.65
$t_{99\%}$ (hours)	112.49	125.72	150.40
$t_{99\%}$ (days)	4.68	5.23	6.26

FEA Simulation of Moisture Diffusion

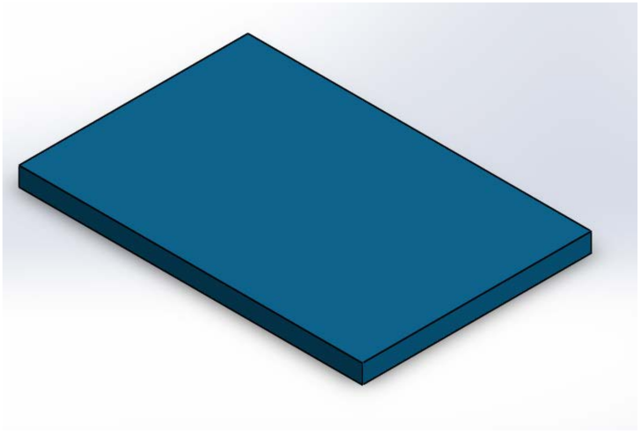
- Fick's moisture diffusion equation follows the same governing differential equation as the diffusion of heat
- Change of the dependent variable, temperature, with moisture concentration and the thermal diffusivity with moisture diffusivity can make any heat transfer simulation software to be used for moisture diffusion problems

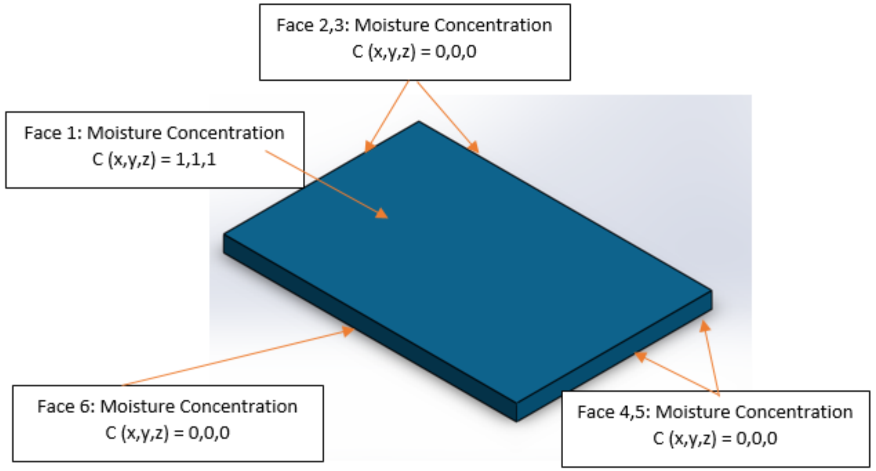
Feature	Heat Transfer	Moisture Diffusion
Field Variables	Temperature, T	Moisture Concentration, C
Density	ρ, density (kg/m^3)	1
Conductivity	K, Conductivity (W/m.ºK)	$D * C_{sat}$ (kg/sec.m)
Specific Heat	c (J/kg ºK)	C_{sat} (kg/m^3)
Thermal Expansion Coefficient	α	$\beta \,.\, C_{sat}$

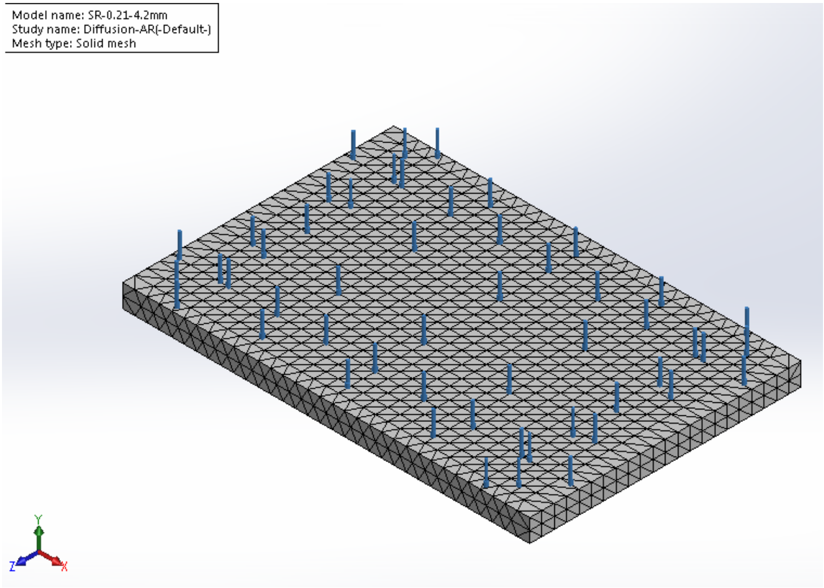
FEA Simulation – Material Properties

	Acrylic		Silicone		FR-4	
	Heat Transfer	Moisture Diffusion	Heat Transfer	Moisture Diffusion	Heat Transfer	Moisture Diffusion
Mass Density (Kg/m^3)	920	1	1200	1	1850	1
Thermal Expansion Coefficient (ppm/K)	1.3E-04	1.4245 ($\beta * C_{sat}$)	5.2E-05	1.1375 ($\beta * C_{sat}$)	60	0.0102 ($\beta * C_{sat}$)
Thermal Conductivity (W/m*K)	0.2	1.6898E-16 ($D * C_{sat}$)	0.158	8.375E-16 ($D * C_{sat}$)	0.3	2.307E-12 ($D * C_{sat}$)
Specific Heat (J/Kg*k)	1470	0.77 (C_{sat})	1507	0.65 (C_{sat})	880	1.02 (C_{sat})

FEA Simulation – Boundary Conditions





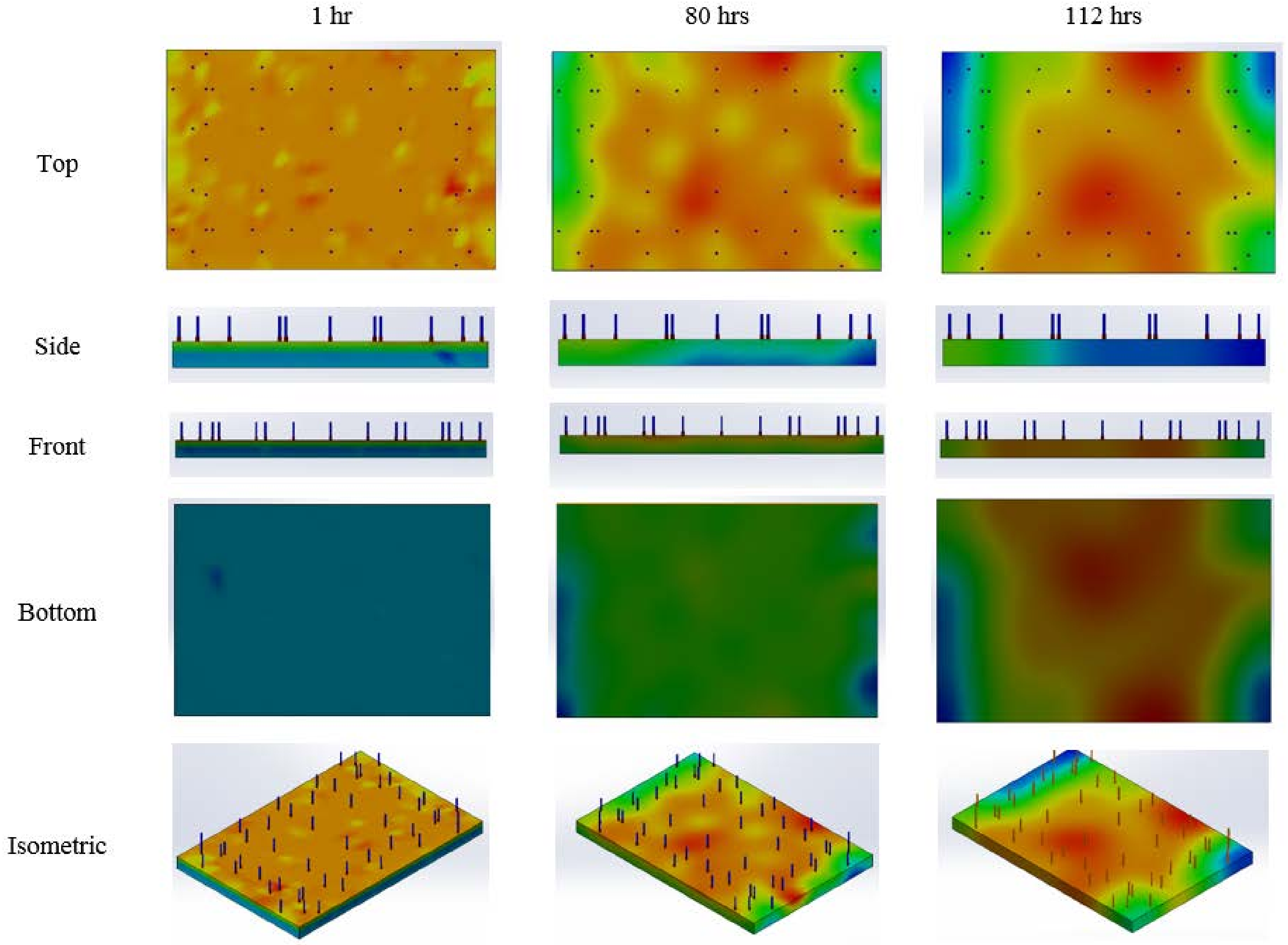


Where;

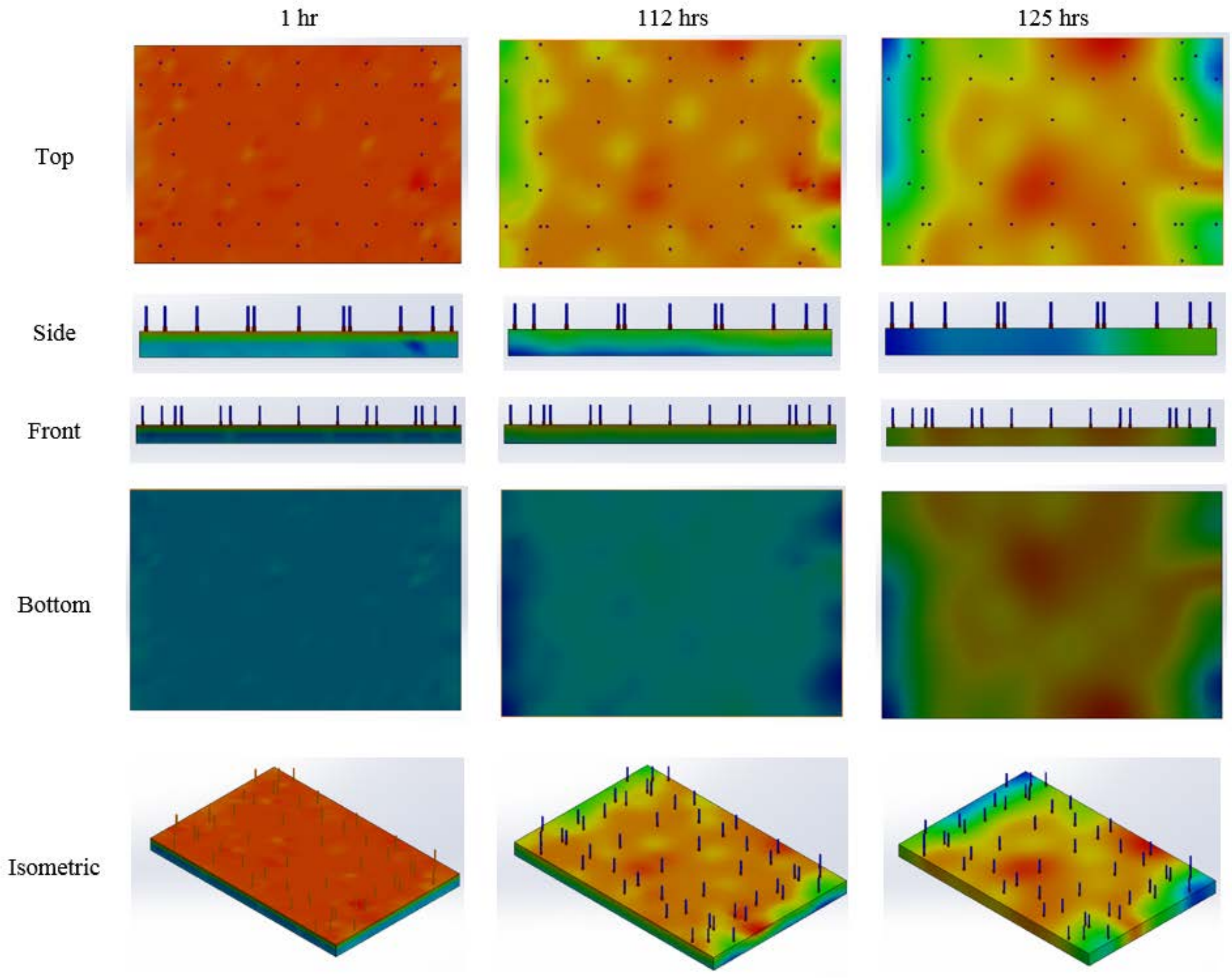
C = 0 for complete dryness

C = 1 for saturated wetness

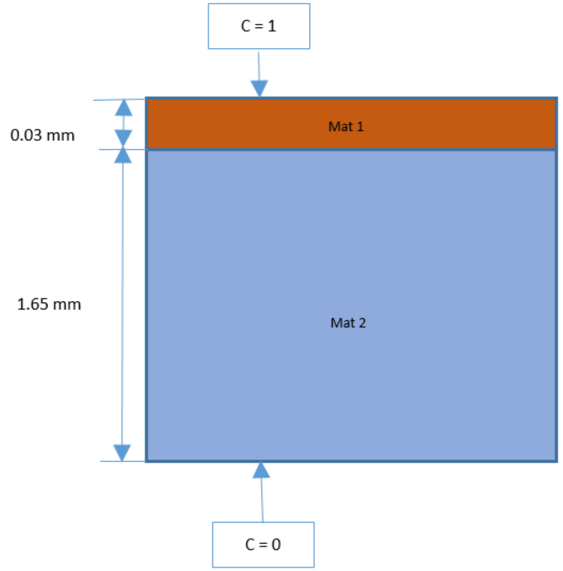
Moisture Diffusion through Acrylic Coating

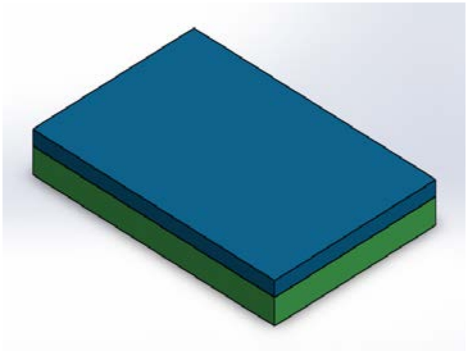


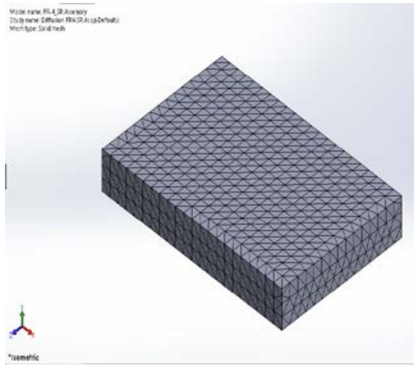
Moisture Diffusion through Silicone Coating

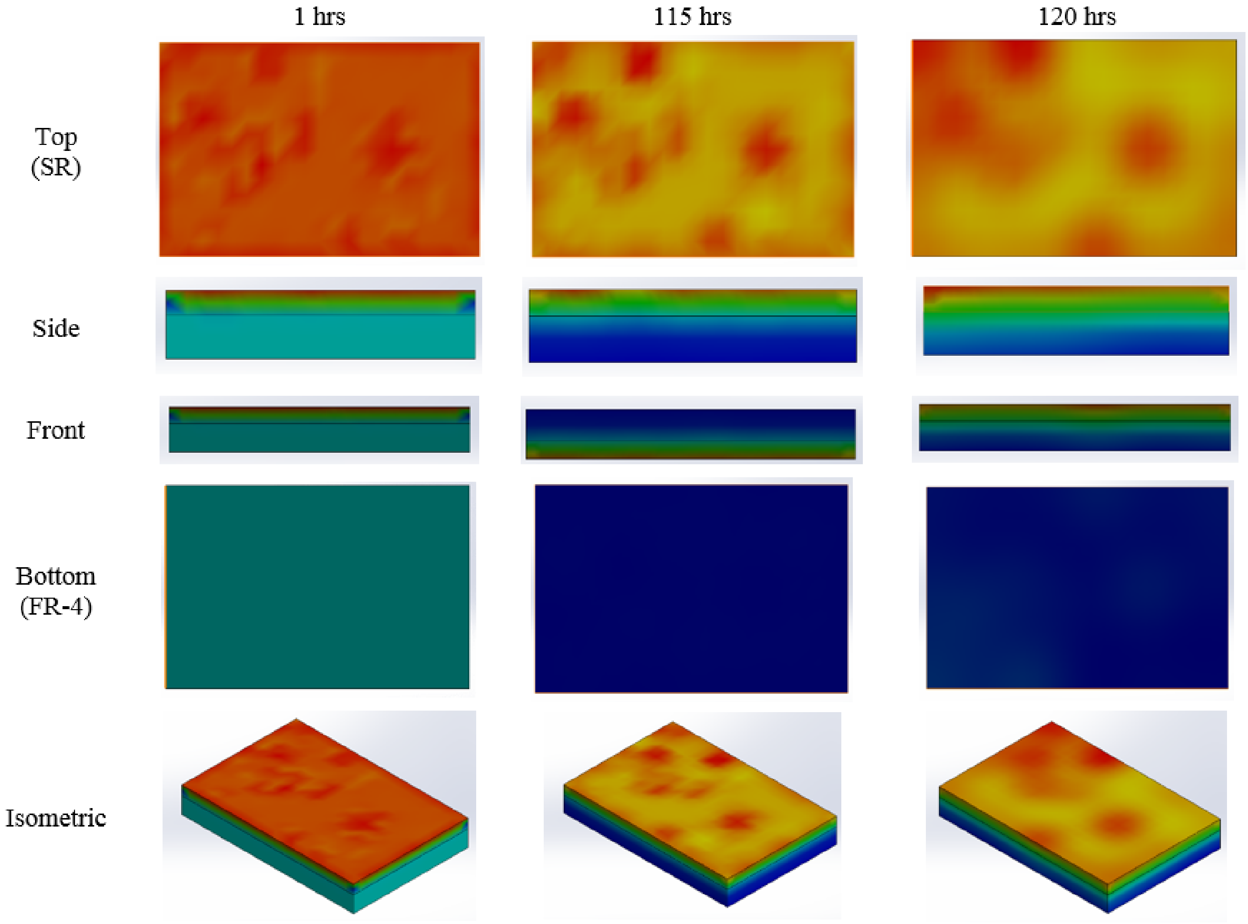


Moisture Diffusion through Acrylic Coating and FR-4 Substrate

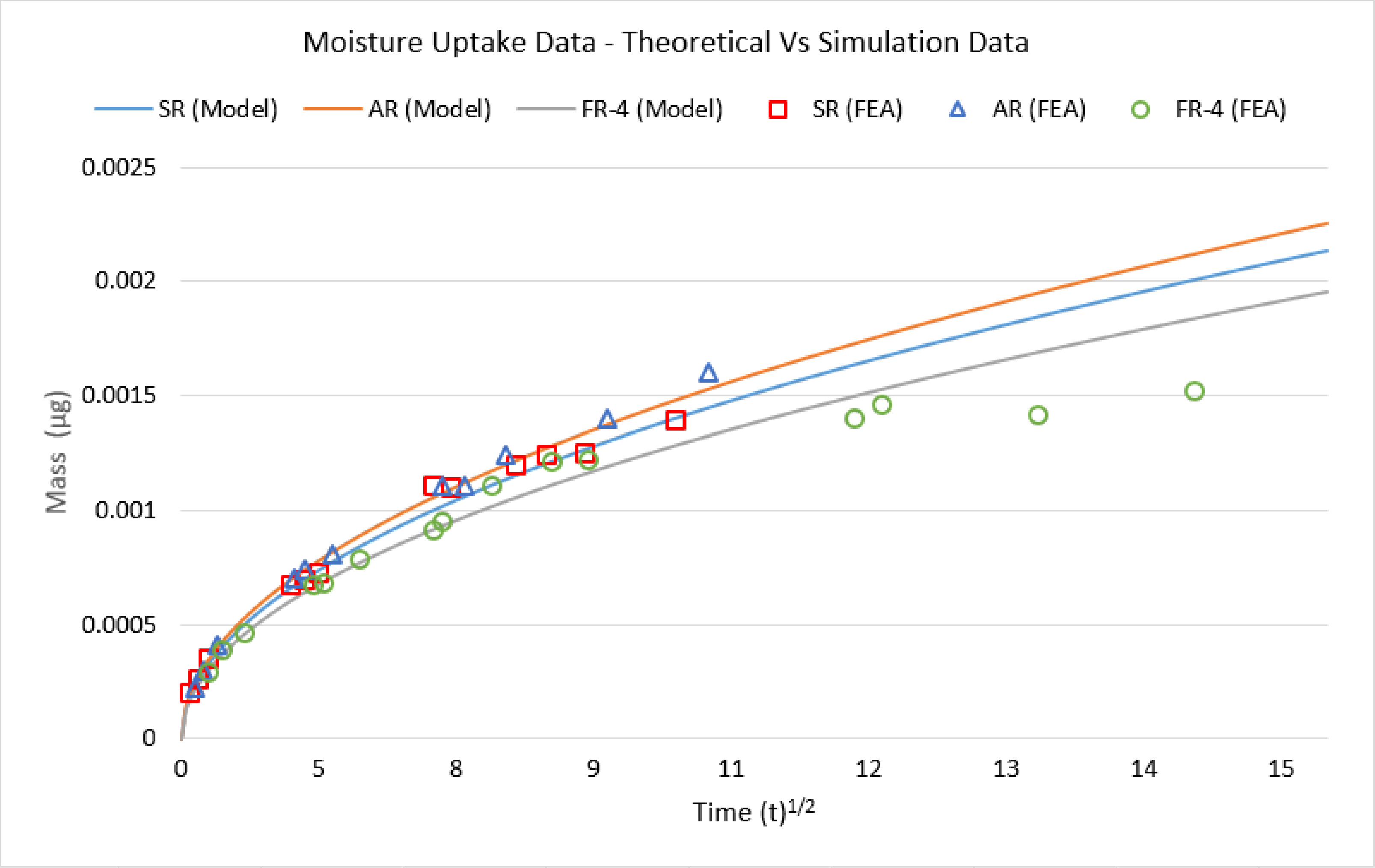








Moisture Uptake Data – Theoretical versus Simulation



Conclusions

- Comparison of moisture diffusion rate between theoretical model and analytical simulation are in reasonable agreement.
- Coefficient of diffusion of materials depends on moisture concentration in the order of magnitudes of thousands of hours as it increases. This information is helpful when specifying bake out cycle for desorption.
- Numerical computations, as shown above allow for calculation of the distribution of moisture concentration, C(t), across the thickness of a material at different times of exposure to humid environments.
- Acrylic resin based coating absorbed more aggregate moisture than Silicone resin based coating.
- Diffusion rate of AR coating is 2.5 times faster than SR coating. It is attributed to the different chemistry in each conformal coating type
- The FEA model shows that moisture will initially reach the interface of coating and PCB using Acrylic conformal coating as compared to Silicone conformal coating. However, due to the higher saturation concentration of acrylic chemistry more moisture will arrive at the interface if exposed to the moist environment for longer durations.

Thank You

Q & A