Effects of Moisture Content on Permittivity and Loss Tangent of Printed Circuit Board Materials

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Abstract
Printed circuit board laminate datasheets provide permittivity (dielectric constant, Dk) and loss tangent (dissipation factor, Df) values that are used for specification and board design. But past studies have shown that these properties vary with changes in the moisture content of the PCB laminate material and a major predicament can arise when material substitutions are made using laminate datasheets as a guide, especially when the data is derived using dissimilar test conditions or methods. For example, initial impedance calculations on the basis of datasheet values may be acceptable, but actual board performance may be significantly different and may result in poorly functioning and unreliable boards.

This experimental study establishes whether the preconditioning steps outlined in the IPC-TM-650 2.5.5.9 (Permittivity and Loss Tangent, Parallel Plate, 1MHz to 1.5 GHz) test standard account for varying moisture contents in PCB laminate test coupons. The moisture content in a PCB material may vary because of material constituents, board design or handling, processing, shipping and end use conditions. Additionally, this study also sheds light on the dependence of dielectric values on moisture content and type of flame retardant used. Commercially available PCB materials sourced from two manufacturers were tested in this study. Materials were classified on the basis of flame retardant type (halogenated or halogen-free) and glass transition temperature. The extent of variation in the dielectric properties is discussed as a function of material constituents and moisture content. The types of materials that are most affected and reasons behind the variation are also reported.

Key words: laminate, moisture, dielectric constant, dissipation factor, halogen-free

1 Introduction

Moisture in electronics is a significant concern for system reliability due to its impact on the electrical properties of dielectric materials. Excess moisture can lead to a reduction in circuit switching speeds and an increase in propagation delay times by increasing the dielectric constant [1]. Certain amounts of moisture can be initially present in the epoxy glass prepregs, moisture is absorbed during the wet chemical processes in the manufacturing steps, or it can diffuse into the printed circuit board during storage [2]. Several papers studying the impact of hydrothermal aging on the dielectric properties of printed circuit board laminates have been published. Dielectric strength or breakdown field, as well as volume and surface resistivity, are reduced by moisture absorption [3-6]. The general tendency for dielectric constant (D_k) and dissipation factor (D_f), based on literature and past work, is an increase in D_k and D_f under the effect of humidity [7-10]. As an example, in pure epoxy it has been observed that the dielectric constant increases by about 10% when the water content is around 1 wt. %, while the dissipation factor increases by about several order of magnitude for the same amount of gain in moisture [10-11]. Therefore, even a small amount of absorbed moisture significantly changes the dielectric properties of printed circuit board laminates, it has been shown that small changes in D_k and D_f has resulted in failure of electronics systems [12-14].

A major problem can arise when material substitutions are made using laminate data sheets as a guide, especially when the data is derived across different laminate test conditions and methods. While initial impedance calculations may look acceptable to the designers because the D_k values are similar, the actual board performance may be significantly different and may result in poorly functioning or non-functioning boards [14].

In the past, CALCE conducted material dielectric properties (D_k and D_f) measurements on PCB materials. Some measurement results were not in accordance with manufacturer datasheets. In the previous study, the tests were conducted as per IPC test methods, including the preconditioning of test samples. This paper is a follow-up to experimental studies of the D_k and D_f on the moisture content of laminates. Four types of PCB materials from two manufacturers, including two halogen-free and two halogenated, were tested in this study. The paper also investigates the suitability of IPC-TM-650 2.5.5.9 for D_k and D_f measurement of printed circuit board laminates with varying moisture contents. We also seek to determine whether the preconditioning steps outlined in the IPC-TM-650 2.5.5.9 test method account for varying moisture contents in PCB laminates.

2 Experimental Details

Four PCB materials—two halogenated (A, C) and two halogen-free (B, D) —were tested. These laminates were acquired from two manufacturers (A and B from manufacturer I and C and D from manufacturer II). The laminates' properties are shown in Table 1 according to their datasheets.

Table 1 Thermal and dielectric properties of test materials

Properties		**A**	**B**	**C**	**D**	**Test Method IPC-TM-650**
z-CTE ppm/ ^oC	below T_g	30-50	50-70	40-55	55-70	2.4.24
	above T_g	200-230	270-300	170-250	170-300	
T_g (^oC)		150 ±5 (DSC)	140 ±5 (DSC)	140-150 (TMA)	135-145 (TMA)	2.4.24 (TMA) 2.4.25 (DSC)
D_k	1 MHz	4.6-4.8	4.2-4.4	4.8-5.0	N/A	2.5.9.9
	1 GHz	4.1-4.3	3.8-4.0	N/A	N/A	
D_f	1 MHz	0.014-0.016	0.015-0.020	0.0060-0.0070	N/A	
	1 GHz	0.012-0.014	0.012-0.014	N/A	N/A	

2.1 Equipment and Test Methods

An Agilent E4991A RF Impedance/Material Analyzer with a 16453A test fixture was used for measuring the D_k and D_f. The internal synthesizer collects data from 1 MHz to 3 GHz with 1 MHz resolution. 1GHz was used in this study. The 16453A test fixture is specifically designed for dielectric constant and dissipation factor measurements on the Agilent E4991A. The E4991A uses a capacitance method to calculate permittivity. The metal electrodes of the 16453A test fixture form the electrodes of a parallel plate capacitor with the sample placed between the two electrodes (Figure 1) as the dielectric. By measuring the capacitance of this system, D_k and D_f can be calculated using relationship shown in equations 1 & 2.

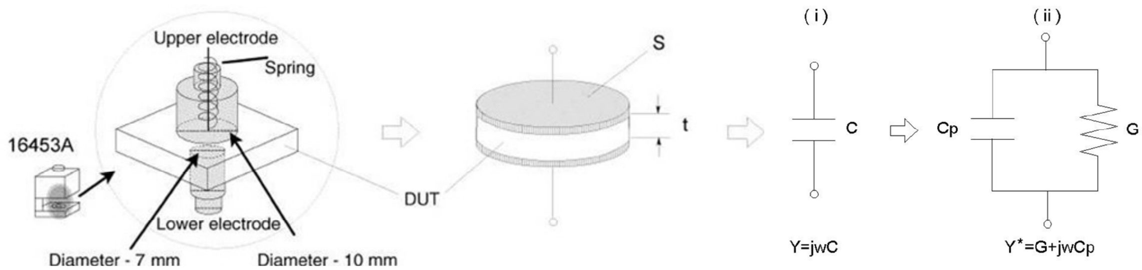


Figure 1 Schematic of capacitor method used in 16453A

$$D_k = \frac{C_p}{C_0} = \frac{tC_p}{\varepsilon_0 S} \qquad (1)$$

$$D_f = \frac{G}{\omega C_0} = \frac{t}{\omega \varepsilon_0 S R_p} \qquad (2)$$

Y= admittance *G=conductance*

t= thickness of test material *S=surface area of lower electrode*

ε_0= permittivity in vacuum *ω= angular frequency*

C_p= capacitance of a capacitor with dielectric in between

C_o =capacitance of a capacitor with vacuum in between

R_p= resistance of a capacitor with dielectric in between

Three coupons of 50mm×50mm of each material were used for this test. With increase in thickness of the sample the exactitude of the measurements results improve. Multilayer samples can be used to increase the thickness, but instead of simply stacking them, they have to be physically bonded together to avoid air gaps between the layers. A target thickness of 1 mm is recommended by the standard, but both thinner and thicker samples would work too, within the limits of the test fixture. The laminates that are used in this project have a thickness around 1mm and so are just fine for this test and no stacking is required.

The tests were run under room conditions. Because materials are affected by moisture, the tests were started within 30mins after the preconditioning process. The test coupons were measured within 1 hour after being taken out of the chamber.

To ensure gap-free contacts between the electrodes of the test fixture and the sample, the right level of force has to be applied to the sample by the upper electrode of the test fixture. If too less pressure applied to the sample, air gaps will lead to wrong measurements. If too high pressure applied to the sample, the sample will be squeezed and the thickness is reduced and therefore unknown, what leads to wrong calculations by the E4991A software. Since the pressure of the test fixture on the specimen affects the measured D_k and D_f values, the pressure was kept uniform in this study.

2.2 Experimental Procedure

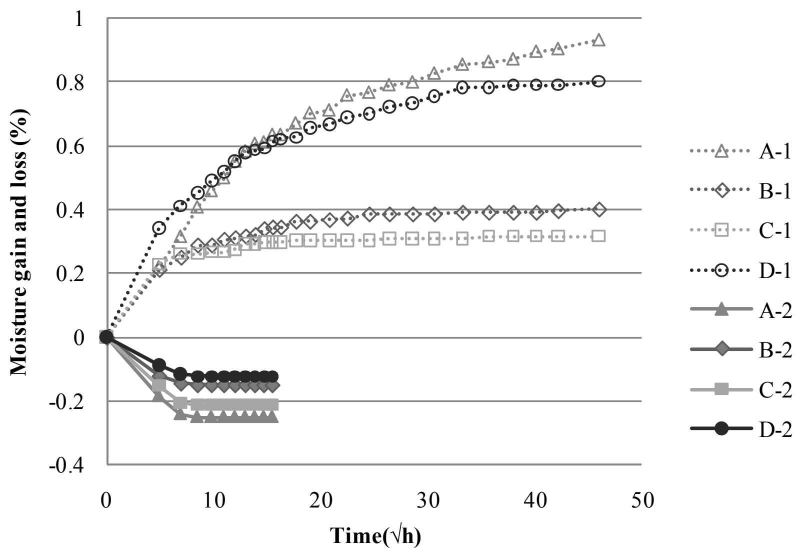
Copper cladded materials which were cut from some laminate were etched to remove copper from the laminate surface. The samples were placed in a solution of water and sodium per sulfate on a hotplate until all the copper was etched from the surface and were then cleaned under running water. The concentration of the solution and the operating temperature were noted on the package of the sodium per sulfate. After etching the samples were dried in an air-circulating oven for two hrs at 105°C. Then the specimens were prepared in order to study the moisture absorption and desorption behavior of the PCB laminates. Based on the results from the absorption and desorption experiments, time intervals were selected for studying the effect of moisture on D_k and D_f, and also investigated the suitability of IPC-TM-650 2.5.5.9 for D_k and D_f measurement of PCB laminates with varying moisture contents.

2.2.1 Moisture Desorption and Absorption Experiments

Moisture absorption and desorption experiments were conducted on two kinds of coupons of each PCB material. These experiments were conducted in order to characterize the moisture absorption and desorption behavior of the samples at different exposure times. The test started from the laminate on the shelf. Moisture desorption experiments were conducted on two coupons made of each PCB material. The coupons were baked at 105ºC in an air-circulating oven and weighed at 24 hrs intervals for weight loss with an analytical balance having a resolution of 0.1mg. Moisture absorption experiments were conducted on two coupons made of each PCB material that were exposed to 85ºC and 85% RH conditions in an environmental chamber. The coupons were taken out of the chamber to measure weight gain at increasing time intervals. The experiment was conducted for 2112 hrs and periodically tested at increasing time intervals. After measuring the weight, the coupons were returned to the chamber within 5 minutes. The moisture absorption and desorption results of four PCB laminates are graphically displayed in Figure 2. Weight gain and weight loss, expressed as a percentage of the laminate's initial weight, M_t, was determined by:

$$M_t(wt\%) = \frac{m_t - m_0}{m_0} \times 100\% \qquad (3)$$

where m_0 is the initial weight of test coupon, and m_t is the weight of test coupon at exposure time *t*.



*-1: moisture absoption in 85ºC and 85% RH ; *-2: moisture desorption at 105ºC

Figure 2 Rate of moisture absorption and desorption for four materials (average values of two test coupons)

The results showed that the moisture absorption and desorption rates in 4 laminates were fairly rapid in the early stages, and the rates decreased with time. Based on the results from the absorption and desorption experiments, time intervals were selected for subjecting test coupons to 85ºC and 85% RH and 105 ºC, respectively.

2.2.2 Effect of Moisture on Dielectric Constant and Dissipation Factor

One set of samples consisting of three test coupons of each PCB material were prepared in order to study the effect of moisture absorption on dielectric constant and dissipation factor. Coupons were exposed to 85ºC and 85% RH conditions in a environmental chamber and were taken out of the chamber at 24, 48, 96, 168, 264, 384, 552, 816, and 1080 hrs. The weights were measured with an analytical balance having a resolution of 0.1 mg, and the thicknesses of the specimens were measured with a digital vernier caliper with a 0.01mm least count. After measuring all these parameters, the coupons were put back into the chamber within 5 minutes.

2.3 D_k and D_f Tests on Laminates with Different Moisture Content Preconditioned as per IPC-TM-650 2.5.5.9 Test Method

Ten sets of D_k and D_f test coupons were prepared for each material (Table 2). Each set has three test coupons. Set 1 was baked at 105°C for 2 hrs and then were conditioned at 23°C and 50% RH for 24 hrs before measurement according to the test method IPC-TM-650 2.5.5.9, [15] "Permittivity and Loss Tangent, Parallel Plate, 1MHz to 1.5 GHz," as a control. Sets 2-4 were baked at 105°C for 24, 48, and 72 hrs, respectively, to release moisture. Then they were conditioned at 23°C and 50% RH for 24 hrs according to the IPC test method before measurement. Sets 5-10 were preconditioned at 85°C and 85% RH to absorb moisture and were taken out of the chamber after 24, 48, 96, 192, 504, and 1200 hrs, respectively. These coupons were baked at 105°C for 2 hrs, and then they were conditioned at 23°C and 50% RH for 24 hrs (23/50/24) before measurement according to IPC-TM-650 2.5.5.9.

Table 2 Preconditioning process of test coupons before D_k and D_f measurements

Set No.	Name	85°C/85% RH (hrs)	105°C (hrs)	23/50/24
1	Control	-	2	√
2	b-24 hrs	-	24	√
3	b-48 hrs	-	48	√
4	b-72 hrs	-	72	√
5	a-24 hrs	24	2	√
6	a-48 hrs	48	2	√
7	a-96 hrs	96	2	√
8	a-192 hrs	192	2	√
9	a-504 hrs	504	2	√
10	a-1200 hrs	1200	2	√

3 Results and Discussion

3.1.1 Moisture Absorption and Desorption

The moisture concentration in laminate increases with the exposure time and approaches equilibrium after several days when exposure to a humid atmosphere. The time to reach the saturation point depends on the thickness of the laminate and the ambient temperature. In this study, the laminates were very thin, therefore, moisture diffusion through the edges was assumed negligible and diffusion was modeled using a one-dimensional Fickian model. For Fickian diffusion in a laminate with thickness ℓ exposed on both sides to the same environment, the moisture content, M_t, at time t, is given by the expression

$$\frac{M_t}{M_\infty} = \frac{4}{\ell}\left(\frac{Dt}{\pi}\right)^{1/2} \qquad (4)$$

Where M_∞ is the equilibrium moisture content, and D is the diffusion coefficient, or diffusivity, given in $(\text{length})^2(\text{time})^{-1}$[16].

Moisture diffusion will only occur through the epoxy, as the reinforcement glass does not readily absorb moisture. And, epoxies can inherently also absorb different moisture content; Also, the varying glass/resin ratios between different PCB constructions will result in a varying moisture concentration and maximum moisture uptake. As a result, the moisture absorption characteristics of PCB materials will vary by epoxy type, construction, and epoxy/fiber content [12].

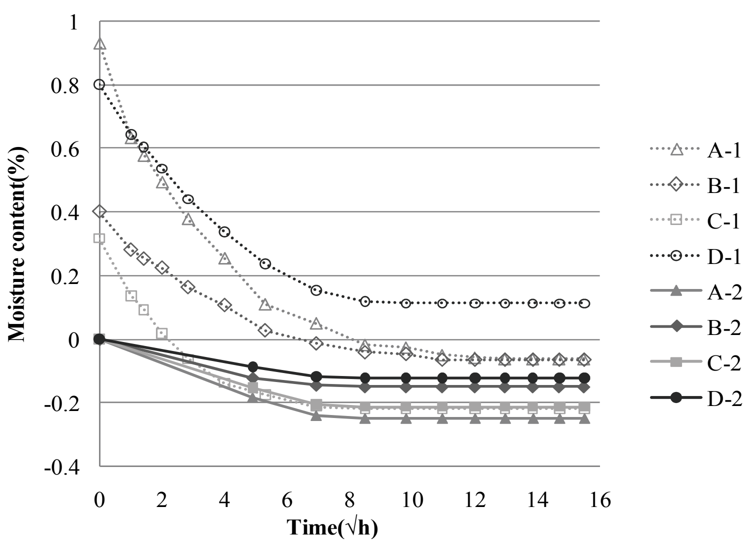
A thermo-gravimetric analyzer was used for measuring the glass/resin ratio for each material. Based on past experience, specimens were subjected to a temperature scan of 25°C to 540°C at a rate of 10^{o}C/min, then held at 540°C for 60 minutes to make the epoxy resin decompose entirely. Calculated results are shown in Table 3.

Table 3: Thickness and glass/resin ratio of four materials

Material	A	B	C	D
Thickness	0.95	1.16	0.69	1.16
Glass/resin ratio	3:1	3:1	4:1	2:1

Moisture desorption experiments were also conducted on the coupons that were exposed to 85°C and 85% RH for 2112 hrs (Figure 2). During 10 days of moisture desorption experiments, the moisture content decreased rapidly in the first 24 hrs. As shown in Figure 4, halogen-free materials A and C released more moisture than halogenated materials B and D in the desorption process starting from the room storage conditions. In other words, halogen-free materials A and C absorb more moisture in room storage conditions. None of the room storage specimens lose weight after baking for 72 hrs, while the specimens which exposure to 85°C and 85% RH for 2112 hrs did not lose weight after baking for 120 hrs.

The water molecules absorbed into the epoxy can be classified into two types [17][18]: bound water and free water. Bound water is trapped at polar sites and is usually bonded to hydroxyl groups in the epoxy network. Free water is clustered in the free volume or voids inside the epoxy. The "free volume" of the polymeric resin is defined as the volume of the resin without the volume of the polymer chains and the volume due to thermal vibrations of the polymer chains. As a result, the moisture content values of coupons which subject to 85°C and 85% RH are higher than the coupons in room storage conditions after baking process, as shown in Figure 3.



*-1: baked from room storage; *-2: baked after being in 85/85 chamber for 2112 hours

Figure 3 moisture desorption behavior at 105°C

3.1.2 Effect of Moisture Absorption on Dielectric Constant and Dissipation Factor

The moisture absorption of PCB laminates and the dielectric constant and dissipation factor as a function of time are shown in Figure 4 and Figure 5. The data represented in Figures 4-11 are averages of the three test coupons. Periodic Dk and Df measurements were conducted on laminate samples originally from a room storage condition to a nearly saturated state at

85°C/85% RH. As shown in Figure 4 and Figure 5, the dielectric constant and dissipation factor increase with the moisture content. Water has extremely polar O-H bonds and a D_k value close to 80. Water molecules will increase the dipole polarization due to polar molecules and interfacial polarization caused by inhomogeneities in the material. Even a small amount of absorbed moisture significantly increases the dielectric properties. Dielectric constant and dissipation factor of a dielectric material are dependent on temperature, frequency of incoming signal, and material content (e.g., moisture) [8].

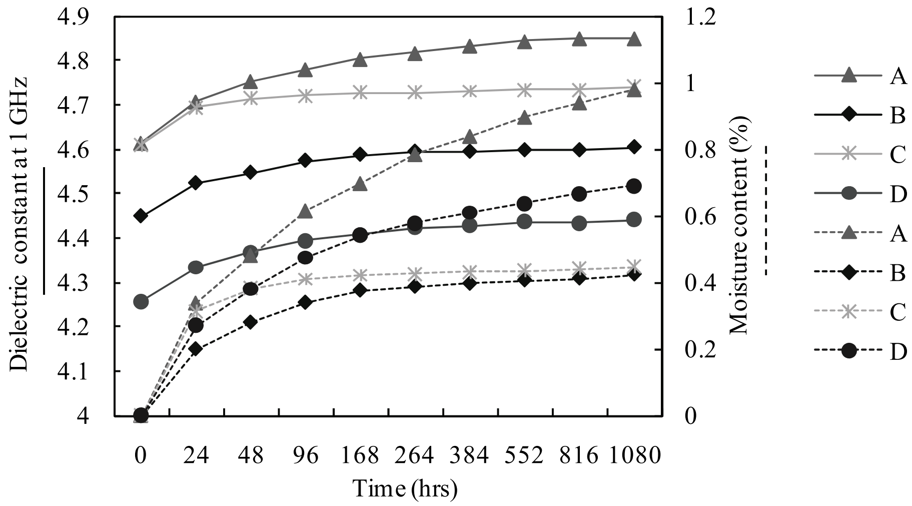


Figure 4 Dielectric constant at 1GHz and absorbed moisture content as a function of exposure time at 85°C/85% RH

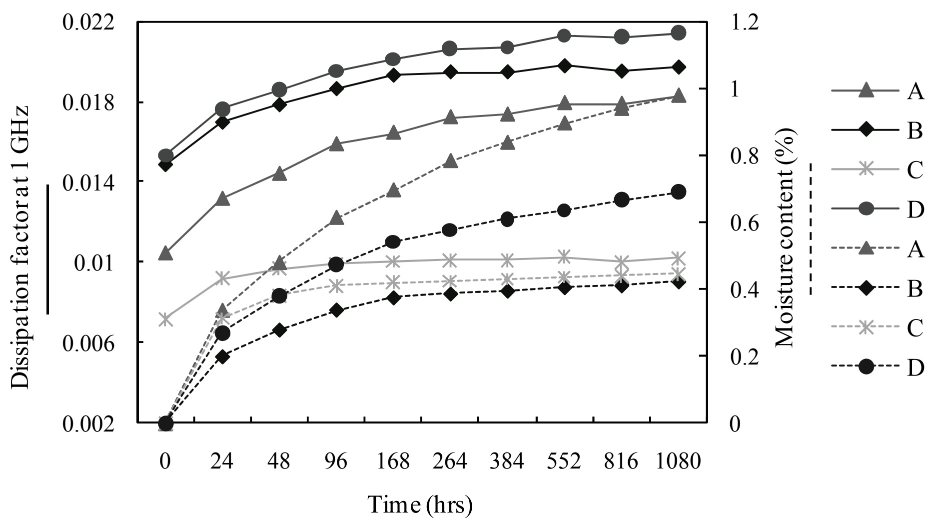


Figure 5 Dissipation factor at 1GHz and absorbed moisture content as a function of exposure time at 85°C/85% RH

The calculated data from Figure 4 and Figure 5 showed that the laminate's D_k and D_f changes with moisture content were linearly proportional (as shown in Figure 6 and Figure 7).

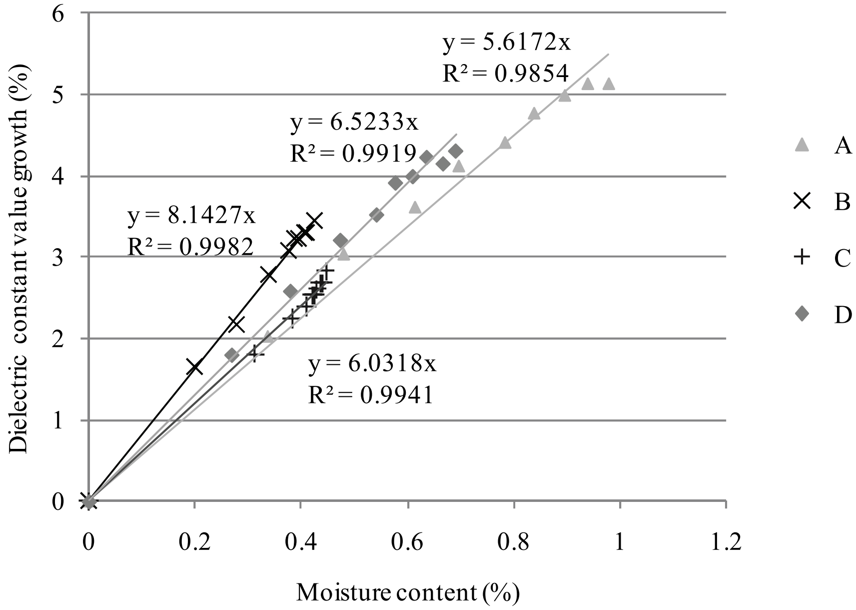


Figure 6 Dielectric constant value changes with different moisture contents

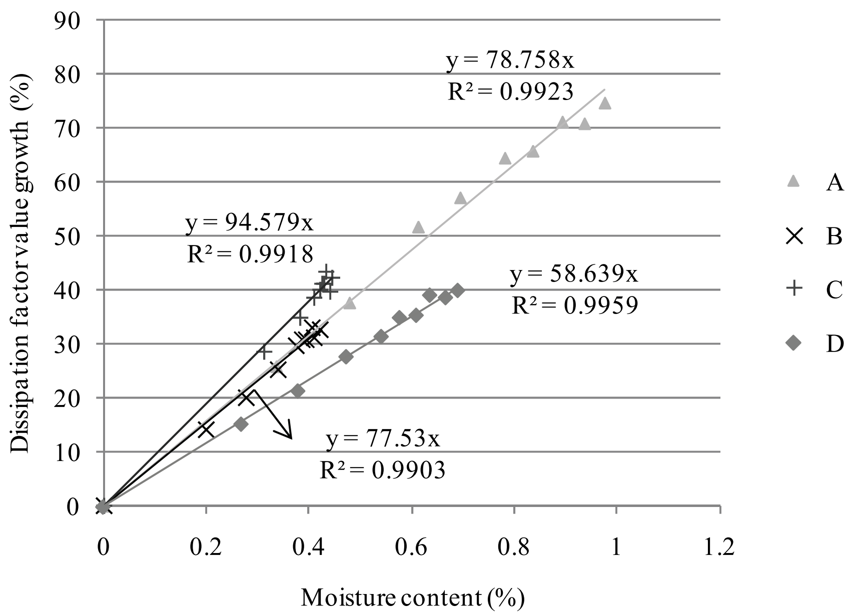


Figure 7 Dissipation factor value changes with different moisture content

Since the data indicated that the two parameters were linearly proportional, two factors were calculated for each laminate to convert the changes in D_k and D_f to moisture content. By the fitting of the data, two equations were derived:

$$\frac{D_{kn} - D_{k0}}{D_{k0}} = \alpha C_w \Leftrightarrow D_{kn} = D_{k0}(1 + \alpha C_w) \qquad (5)$$

$$\frac{D_{fn} - D_{f0}}{D_{f0}} = \kappa C_w \Leftrightarrow D_{fn} = D_{f0}(1 + \kappa C_w) \qquad (6)$$

where D_{kn} and D_{fn} are the effective dielectric constant and dissipation factor of moisture absorbing laminate; D_{k0} and D_{f0}, are the dielectric constant and dissipation factor of the initial laminate; α and κ are factors of the dielectric constant and dissipation factor per unit moisture content; and C_w is the moisture content. The C_w was obtained from the previous weight gain experiment.

The factor α and the factor κ per 1 wt% water content at 85°C and 85%RH were gotten by fitting the data. The results are shown in Table 4. The rate of diffusivity and the equilibrium moisture content can be calculated using Fick's Law of Diffusion using a specific resin system and thickness [14][16]. The dependence of D_k and D_f value on moisture can be used for comparison between PCB materials and to predict the influence of ambient humidity on the overall performance of the system.

Table 4: The factor α and the factor κ per 1 wt% water content at 85°C and 85%RH

Material	**α**	R^2	**κ**	R^2
A	5.6172	0.9854	78.758	0.9923
B	8.1427	0.9982	77.53	0.9903
C	6.5233	0.9919	94.579	0.9918
D	6.0318	0.9941	58.639	0.9959

3.1.3 D_k and D_f Results of Laminates with Different Moisture Content Preconditioned by IPC-TM-650 2.5.5.9 Test Standard

Ten sets of coupons were baked at 105°C or exposure to 85°C/85% RH for various lengths of time to get different initial moisture contents, as shown in Table 2. These coupons were then baked at 105°C for 2 hours, followed by conditioning at 23°C/50% RH for 24 hrs according to the IPC-TM-650 2.5.5.9 test standard before D_k and D_f measurement. The results are shown in Figure 8 and Figure 9. The calculated results of the laminate's D_k and D_f variation compared with the control set are shown in Figure 10 and Figure 11.

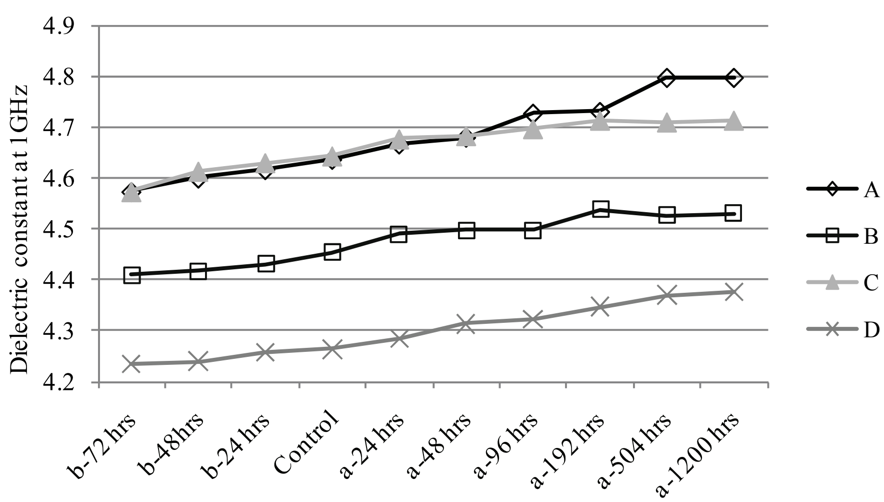


Figure 8 Dielectric constant values in different moisture test conditions

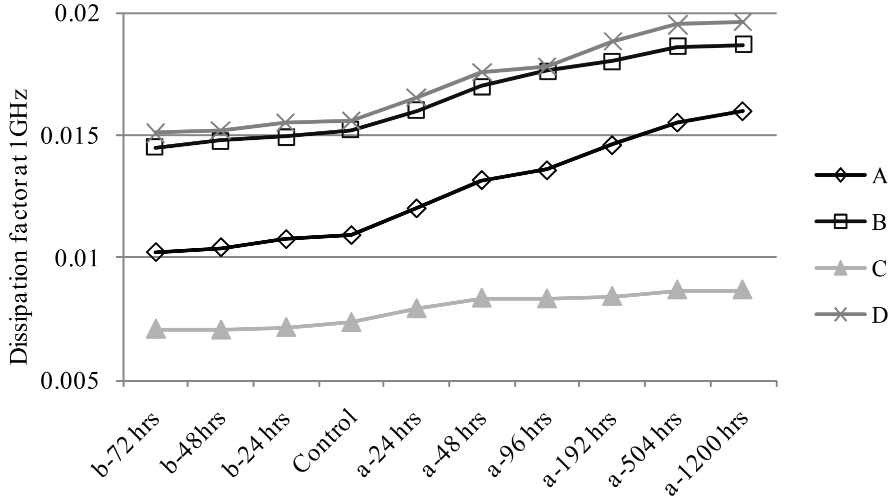


Figure 9 Dissipation factor values in different moisture test conditions

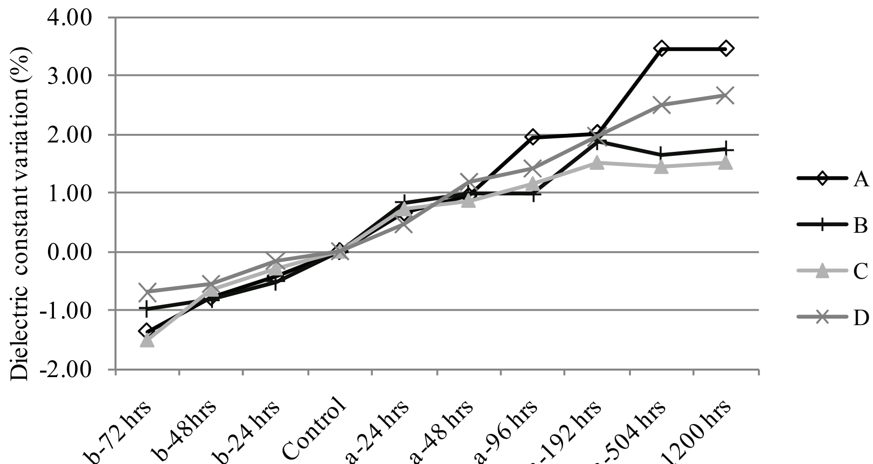


Figure 10 Dielectric constant variation in different moisture test conditions

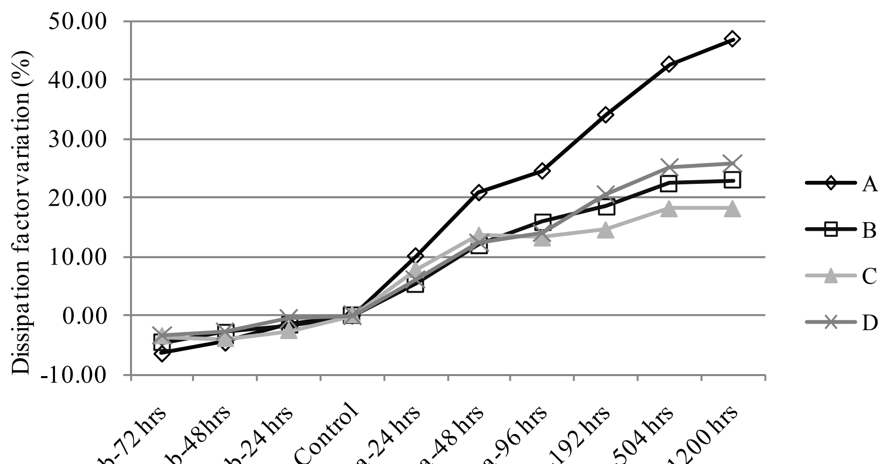


Figure 11 Dissipation factor variation in different moisture test conditions

As received from above figures, D_k and D_f increase with the increase moisture content in laminates. Baking for 2 hours cannot get rid of the majority of moisture that the laminate absorbed in the 85/85 chamber. The D_k still increased ~3.5%

while the D_f increased ~46.7% compared with the control set after preconditioning according to the IPC-TM-650 2.5.5.9 test standard. The preconditioning procedure outlined in the IPC-TM-650 2.5.5.9 test standard cannot account for different moisture contents.

4 Conclusions

This paper presents a follow-up to experimental studies on the dependence of dielectric constant and dissipation factor on the moisture content of laminates. Four types of PCB materials from two manufacturers, including two halogen-free and two halogenated were tested in this study. The results showed that dielectric constant and dissipation factor increase linearly with an increase in moisture content in the PCB laminates. The halogen-free material from manufacturer I absorbed more moisture than all other material tested in this study and had the greatest change in the D_k (5.13%) and D_f (74.5%) values. Halogenated material from manufacturer I and halogen-free material from manufacturer II absorb the least moisture among all the material tested in this study. Halogen-free material from manufacturer II had the smallest change in D_k (2.82%) value, while halogenated material from manufacturer I had the smallest change in D_f (32.5%) value.

The paper also establishes whether preconditioning steps outlined in the IPC-TM-650 2.5.5.9 test standard account for varying moisture contents in laminate samples. For this purpose, ten sets of twelve test coupons, each with different moisture contents were preconditioned as per the IPC-TM-650 2.5.5.9 test standard before the test. The results showed that the preconditioning procedure outlined in the IPC-TM-650 2.5.5.9 test standard does not account for different moisture contents. The dielectric constant and dissipation factor still increase with an increase in moisture content in the PCB laminates. Halogen-free material (manufacturer I) had the largest change in the D_k (3.5 %) and D_f (46.7%) values, while halogen-free material (manufacturer II) had the smallest change in the D_k (1.51%) and D_f (18.2%) values, compared with the control set after preconditioning according to the IPC-TM-650 2.5.5.9 test standard.

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Background and Motivation

- In the past CALCE conducted material property measurements on PCB materials.
  - The measurements were conducted as per IPC standards, including preconditioning of test sample.
  - The measurement results did not match manufacturers datasheets.
- A major problem can arise when material substitutions are made using laminate data sheets as a guide, especially when the data is derived from different laminate test conditions and methods.
  - Initial impedance calculations on basis of datasheet values may be acceptable, but actual board performance may be significantly different and may result in poorly functioning or non-functioning boards [1].

[1] Richard Pangier and Michael J. Gay, "Making sense of laminate dielectric properties", Printed Circuit Design & Fab, January 2009.

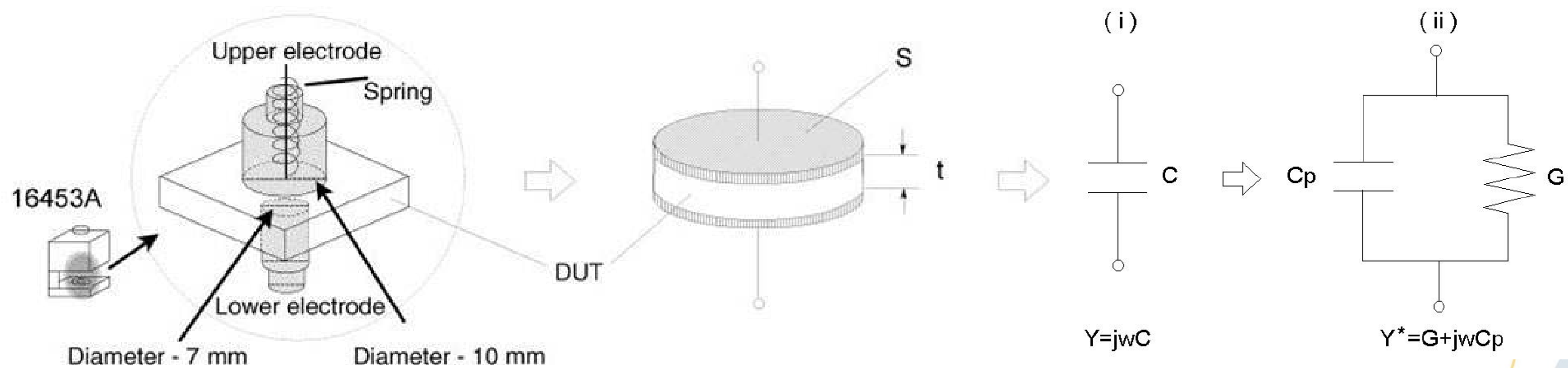
Introduction

- Dielectric constant (D_k) of a material is the ratio of the capacitance of a capacitor containing a particular material to the capacitance of the same electrode system in vacuum.
  - The dielectric constant of printed circuit board materials varies from 2 to 10.
- Dissipation factor (D_f) is ratio of the power loss in a dielectric material to the total power transmitted through the dielectric.
- Dielectric constant and dissipation factor are dependent on temperature, frequency of incoming signal, and material content (e.g. moisture) [2].

[2] Khan, S., "Comparison of the dielectric constant and dissipation factors of non-woven aramid/FR4 and glass/FR4 laminates", Circuit World, volume: 26 Issue: 2, pp 33-37, June 2000.

Equipment and Test Methods

- Agilent E4991A RF Impedance/Material Analyzer with a 16453A test fixture
- Frequency from 1 MHz to 3 GHz.
- A capacitance method is used to calculate D_k and D_f



$$D_k = \frac{C_p}{C_0} = \frac{tC_p}{\varepsilon_0 S}$$

$$D_f = \frac{G}{\omega C_0} = \frac{t}{\omega \varepsilon_0 S R_p}$$

Y= admittance
G=conductance
ω= angular frequency
C_p= capacitance of a capacitor with dielectric in between
C_o =capacitance of a capacitor with vacuum in between
ε_0= permittivity in vacuum
S=surface area of lower electrode
t= thickness of test material

Materials

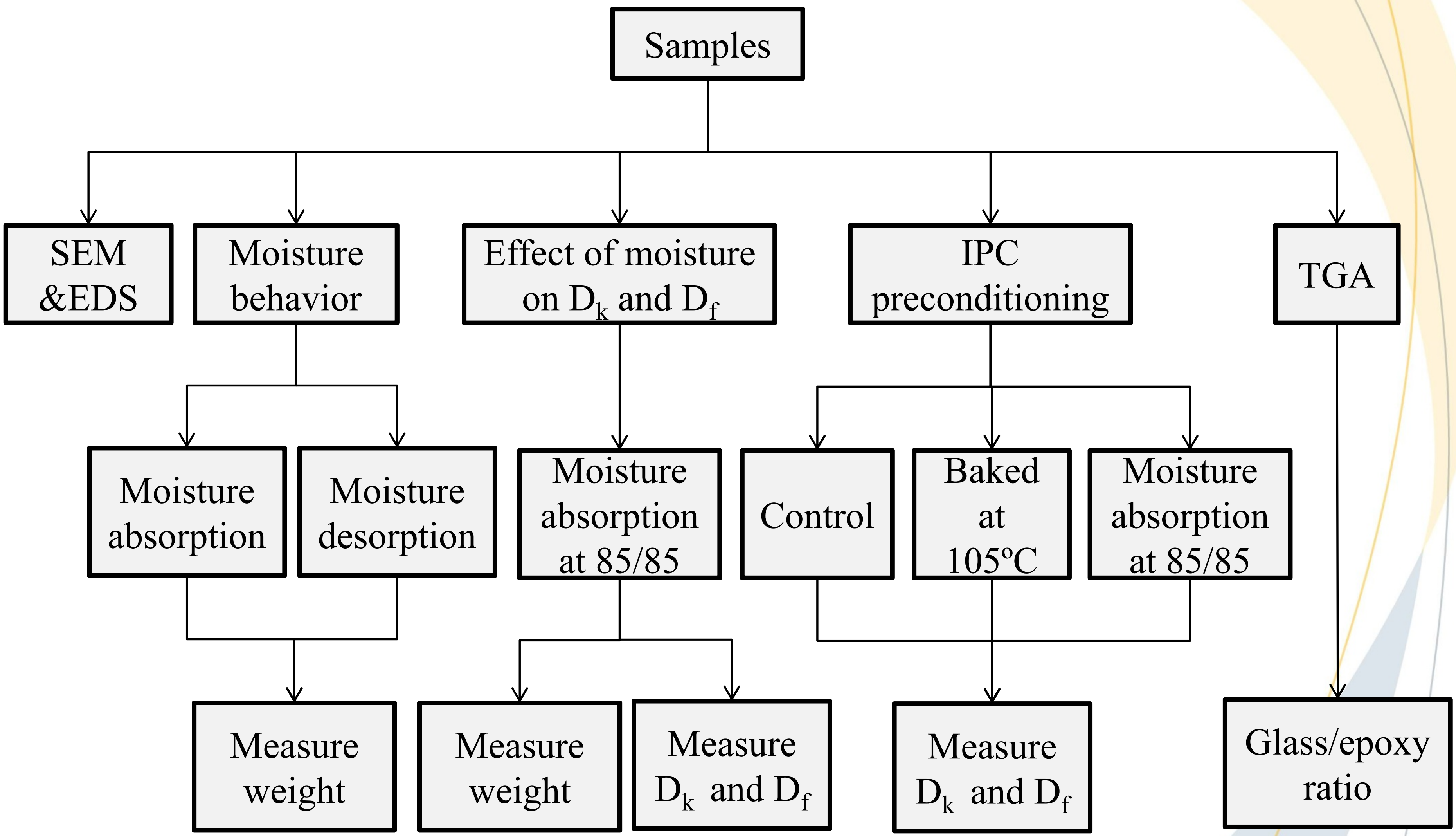
Four PCB materials — two halogen-free (A, C) and two halogenated (B, D) — were tested. These laminates were acquired from two manufacturers (A and B from manufacturer I and C and D from manufacturer II).

Datasheet values of test materials

Properties		A	B	C	D	Test Method IPC-TM-650
D_k	1 MHz	4.6-4.8	4.2-4.4	4.8-5.0	N/A	2.5.5.9
	1 GHz	4.1-4.3	3.8-4.0	N/A	N/A	
D_f	1 MHz	0.014-0.016	0.015-0.020	0.0060-0.0070	N/A	
	1 GHz	0.012-0.014	0.012-0.014	N/A	N/A	

N/A: not available

Experiments Test Matrix



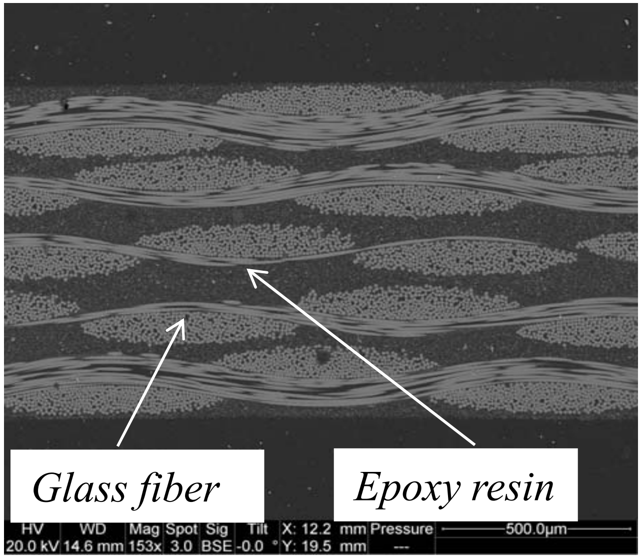
ESEM/EDS and TGA Inspection

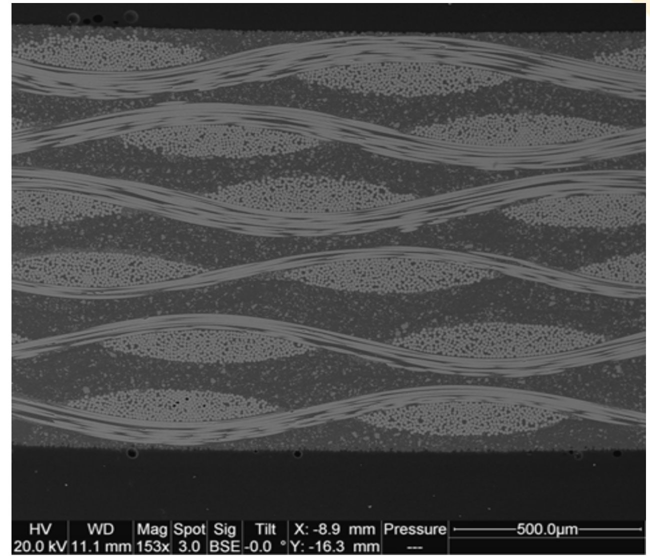
- Environmental scanning electron microscope (ESEM) observation for obtaining laminate information.
- Energy dispersive spectrometry (EDS) was used to identify some flame retardant elements.
  - Manufacturer datasheets do not disclose the type of flame retardant used.
- Thermo-gravimetric analyzer (TGA) was used to obtain the glass/epoxy ratio.

ESEM/EDS and TGA Results

A:
5 plies
0.95 mm total
Halogen-free

Glass/epoxy =3:1



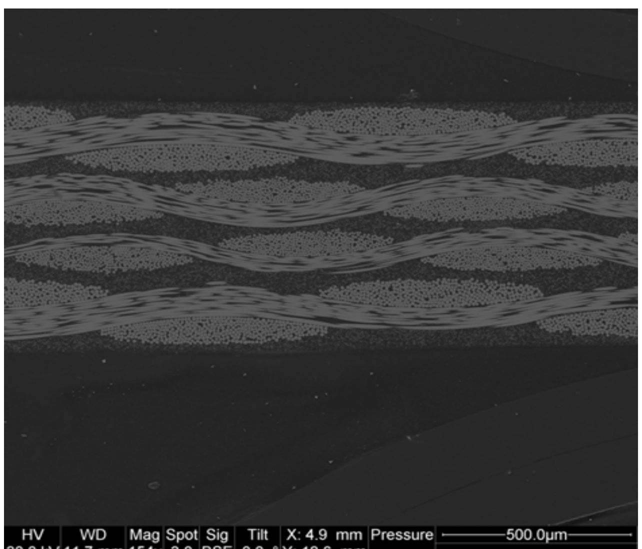


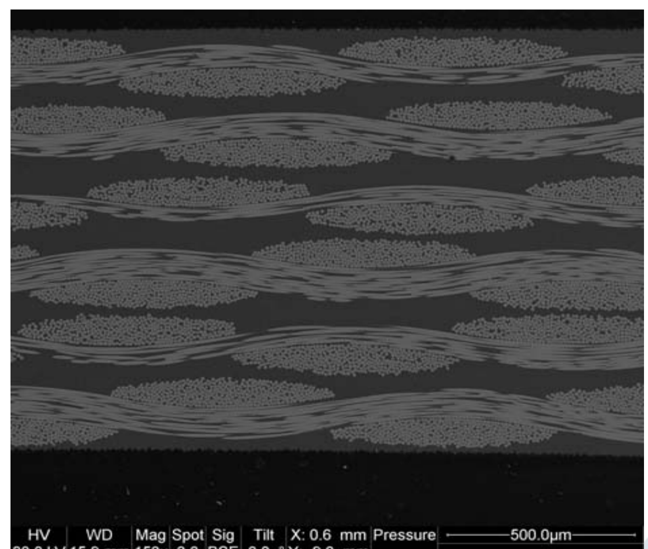
B:
6 plies
1.16 mm total
Bromated

Glass/epoxy =3:1

C:
4 plies
0.69 mm total
Halogen-free

Glass/epoxy =4:1

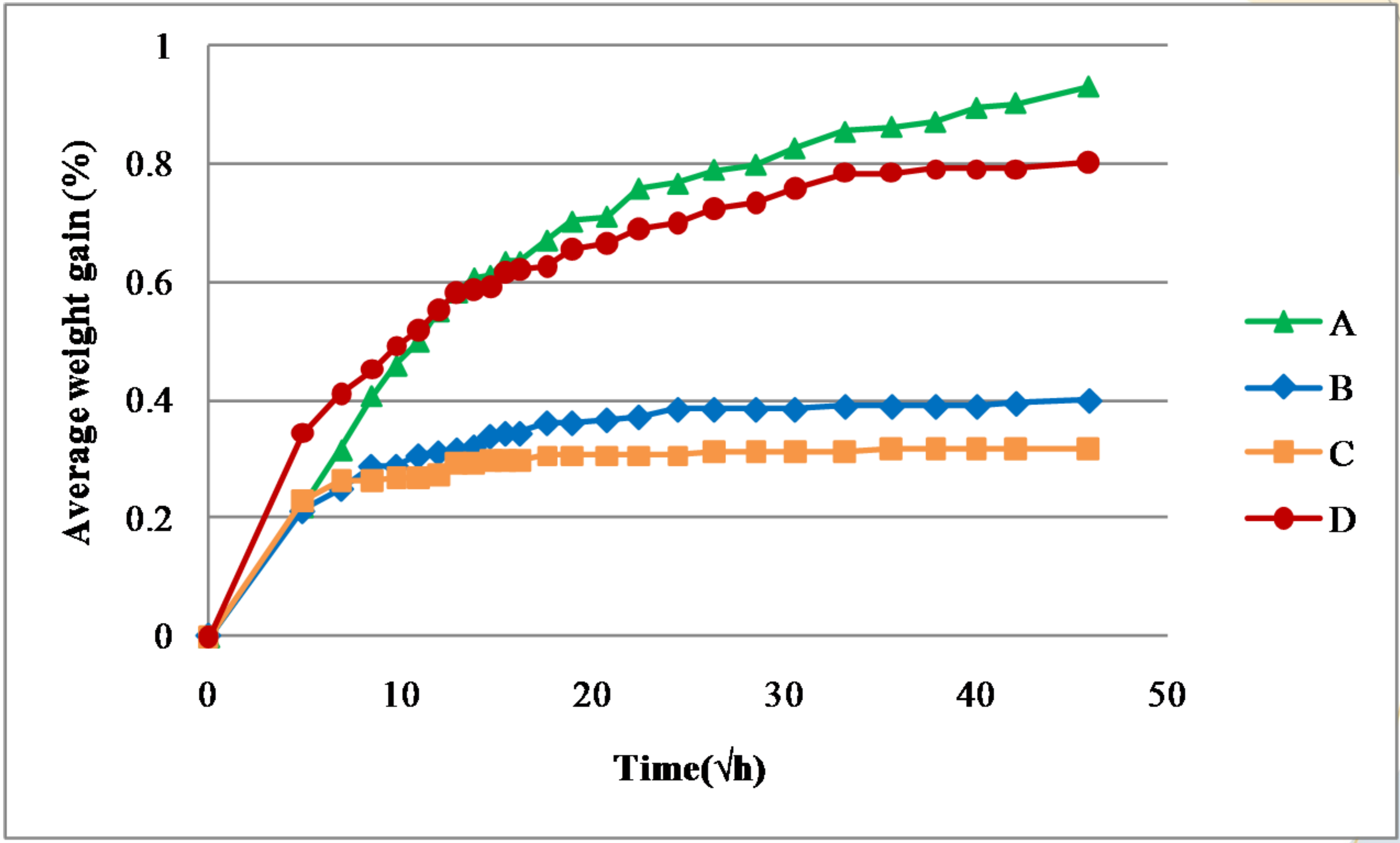




D:
6 plies
1.16 mm total
Bromated

Glass/epoxy =2:1

Moisture Absorption Experiment



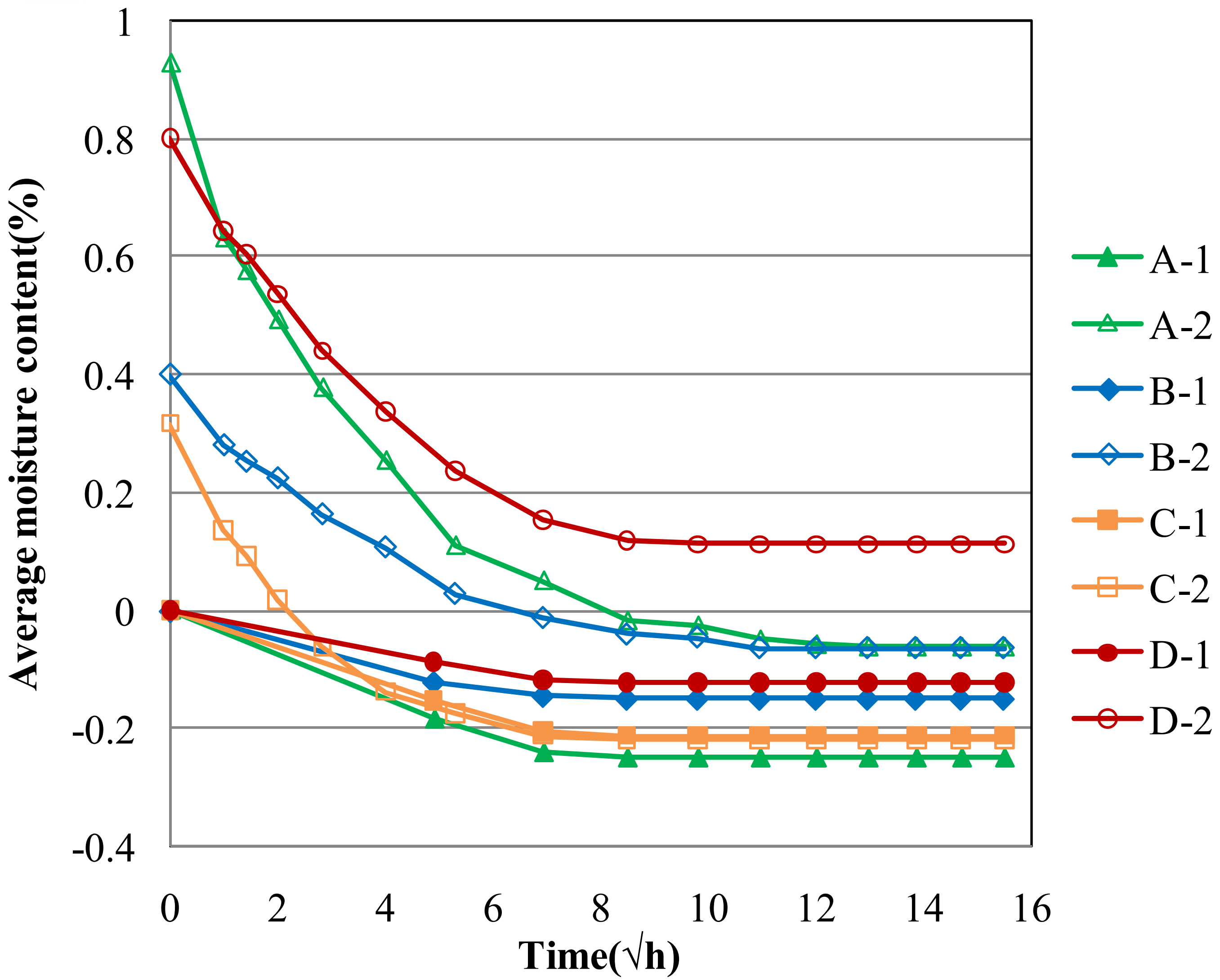
Moisture absorption experiments were conducted on two coupons (10mm×10mm and 20mm×20mm) of each PCB material which were exposed in 85ºC and 85% RH condition and the coupons were taken out of chamber to measure weight at increasing time intervals.

Moisture Absorption

- Moisture diffusion occurs into the epoxy, as the reinforcement glass does not readily absorb moisture [3].
  - As a result, the moisture absorption characteristics of PCB dielectric materials will vary by construction and epoxy/fiber content.
  - The glass reinforcement will act as a barrier to restrict flow and impact the diffusivity between different constructions.
  - Also, the varying glass/resin ratios between PCB different constructions will result in a varying moisture concentration and maximum moisture uptake.

[3] Hamilton, P.; Brist, G.; Guy Jr, B.; and Schrader, J., "Humidity-Dependent Loss in PCB Substrates," Proceedings of IPC Printed Circuit Expo, February 2007.

Moisture Desorption Experiment



Moisture desorption experiments were baked at 105ºC on two kinds of specimens:
1.baked from room storage condition.
2.baked after moisture absorption in 85/85 for 2112 hours.

Upon bake, test coupons did not release all moisture absorbed during 85ºC/85%RH exposure.

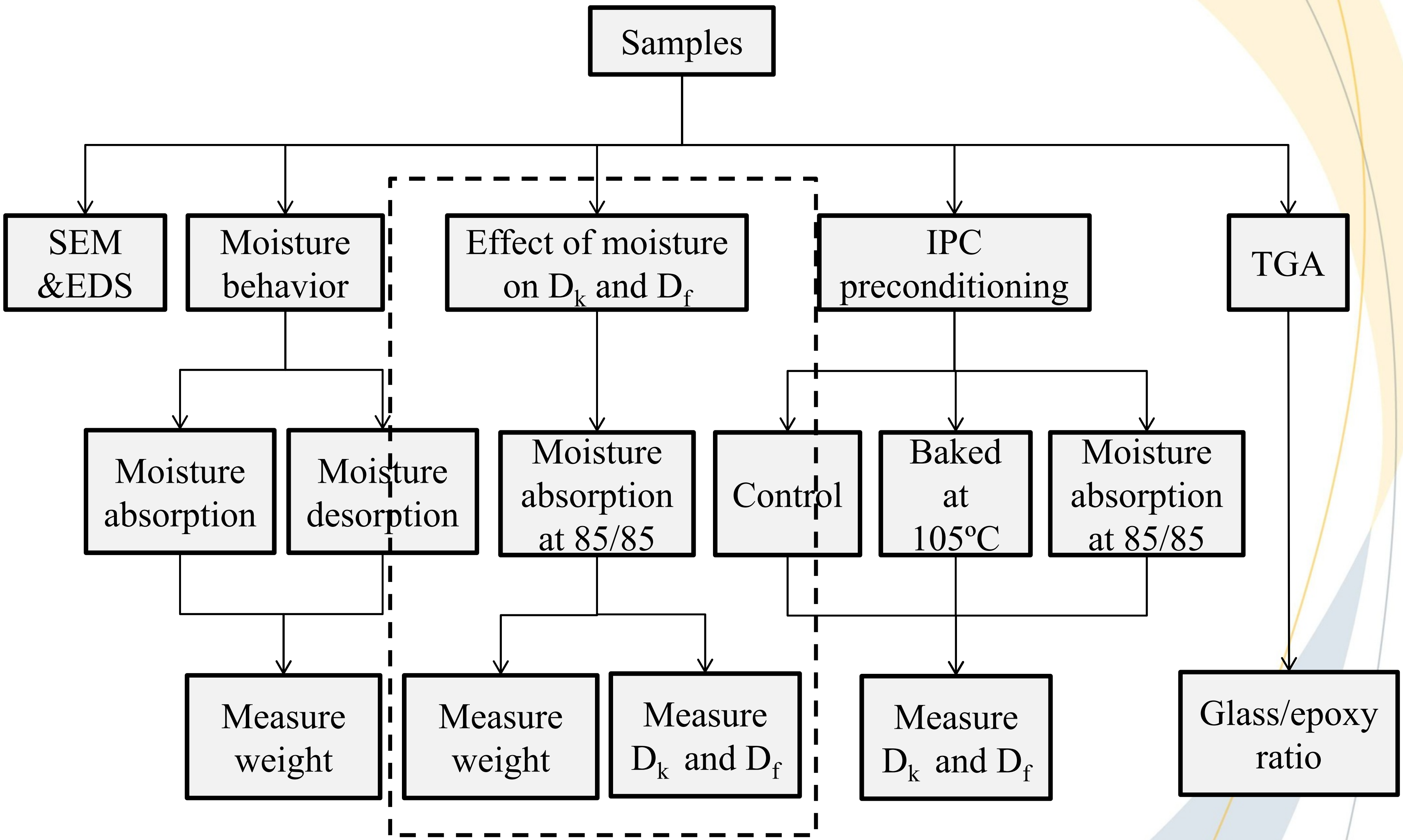
Moisture absorbed in Laminate

- The water molecules absorbed into epoxy can be classified into two types [4, 5]:
  - ‘‘bound’’ water which is trapped at polar sites that is usually bonded to hydroxyl groups in the epoxy network;
  - ‘‘free’’ water which is clustered in the free volume or voids inside the epoxy.

[4] Zhao, H.; and Li, Robert K.Y., "Effect of water absorption on the mechanical and dielectric properties of nano-alumina filled epoxy nanocomposites", Composites. Part A, Applied science and manufacturing, v 39, n 4, pp: 602-611, 2008.

[5] Maggana, C.; and Pissis, P., "Water sorption and diffusion studies in an epoxy resin system", Journal of polymer science. Part A, Polymer chemistry, v37, n 11, pp: 1165-1182, 1999.

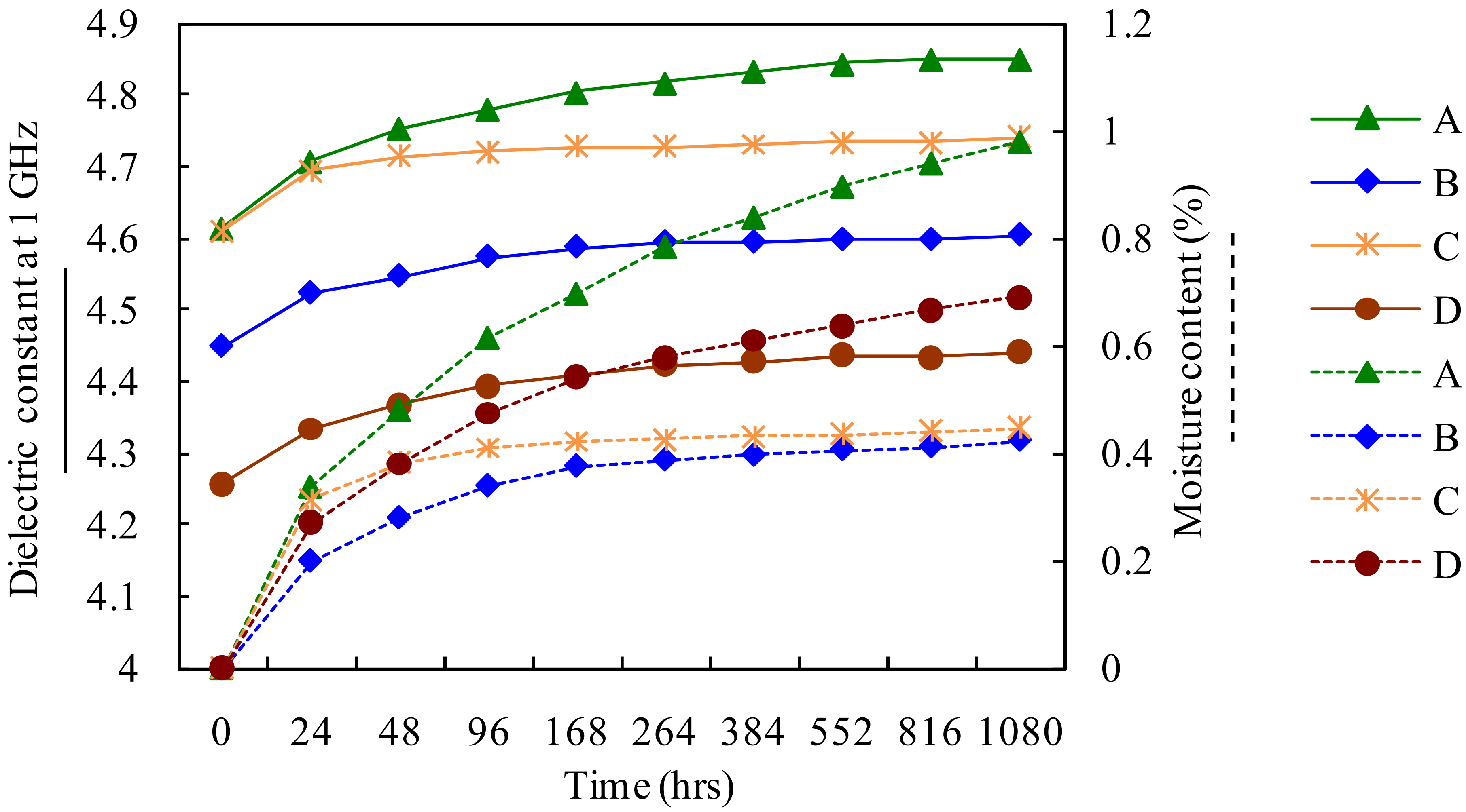
Experiments Test Matrix



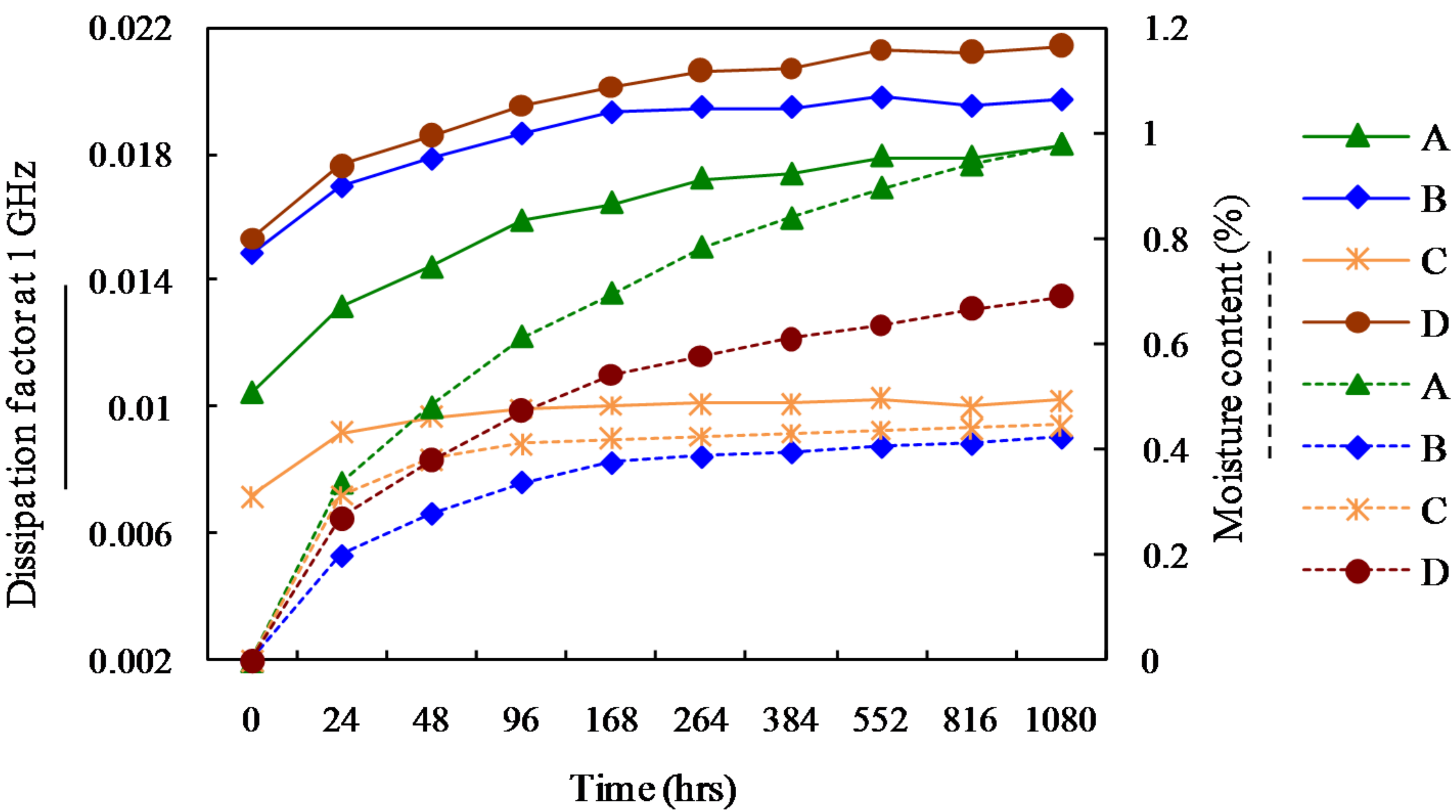
Effect of Moisture on D_k and D_f

1. Prepare 1set D_k and D_f test coupons (50mm×50mm).
2. All coupons were conditioned at 85° C and 85% RH chamber and were taken out of 85/85 chamber respectively at 24, 48, 96, 168, 264, 384 hrs ……, weigh the coupons and measure D_k and D_f.

Effect of Moisture on D_k

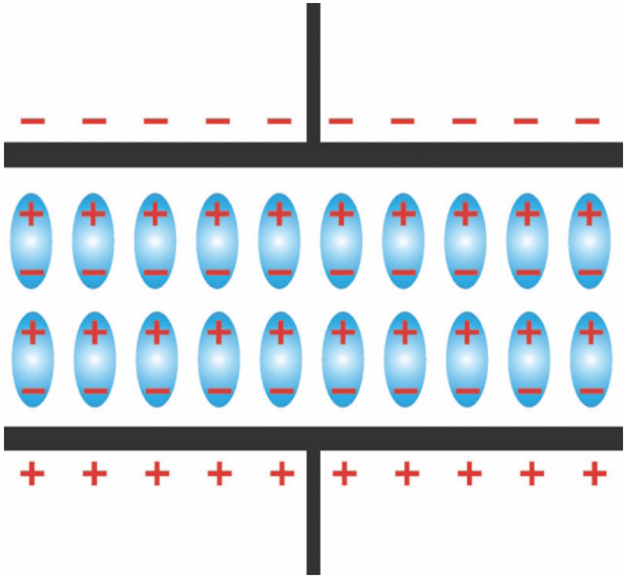


Effect of Moisture on D_f



Effect of Moisture on D_k and D_f

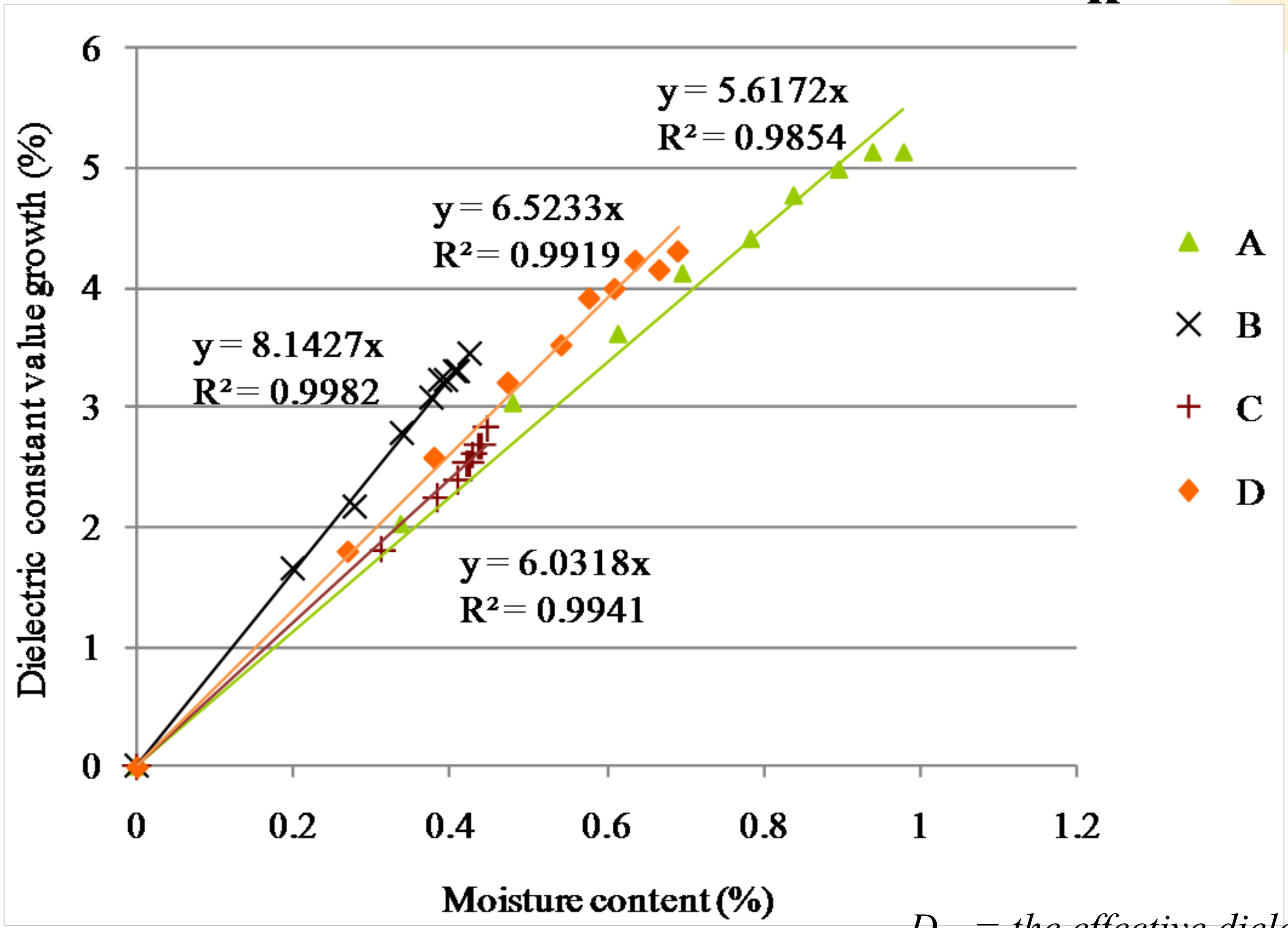
- Water has extremely polar O-H bonds and a D_k value close to 80. Water molecules will increase the dipole polarization due to polar molecules and interfacial polarization caused by inhomogeneities in the material.
- Even a small amount of absorbed moisture significantly increases the dielectric properties.



Schematic view of a capacitor

A capacitor with a dielectric medium of higher D_k will hold more electric charge at the same applied voltage. In other words, its capacitance will be higher.

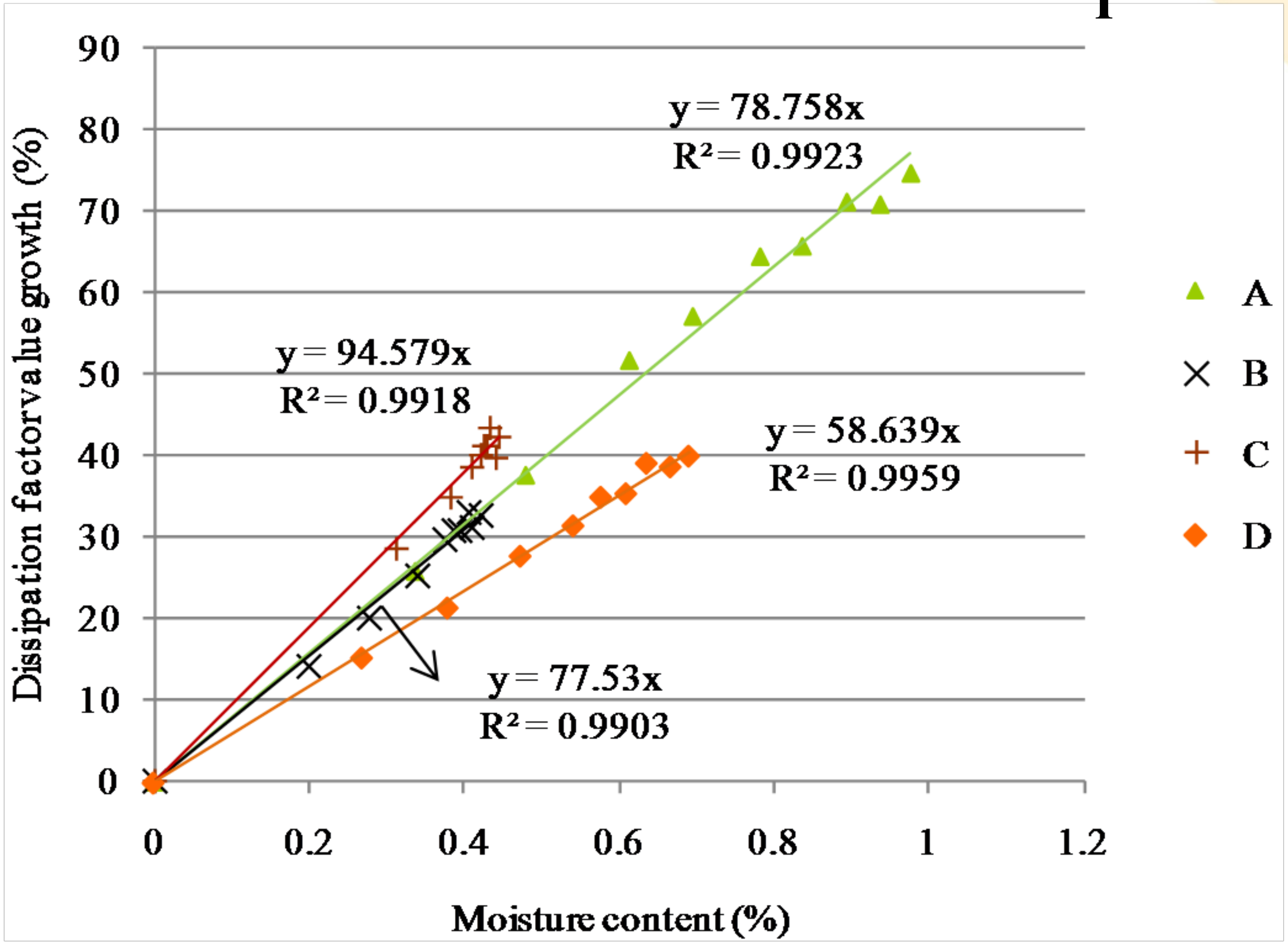
Effect of Moisture on D_k



$$\frac{D_{kn} - D_{k0}}{D_{k0}} = \alpha C_w \Leftrightarrow D_{kn} = D_{k0}(1 + \alpha C_w)$$

D_{kn} = *the effective dielectric constant*
D_{k0} = *the initial dielectric constant*
α = *factor*
C_w = *the moisture content*

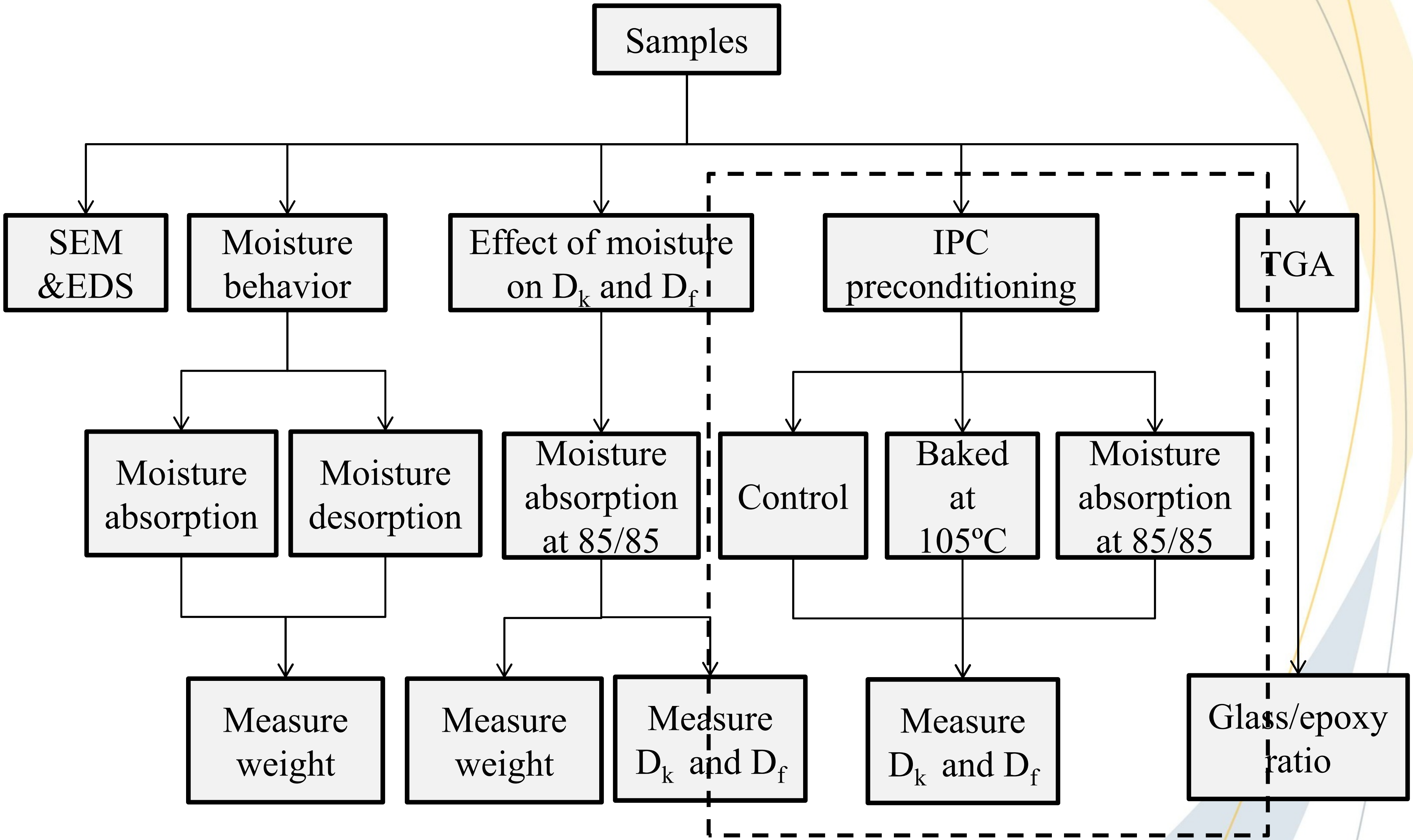
Effect of Moisture on D_f



$$\frac{D_{fn} - D_{f0}}{D_{f0}} = \kappa C_w \Leftrightarrow D_{fn} = D_{f0}(1 + \kappa C_w)$$

D_{fn} = *the effective dissipation factor*
D_{f0} = *the initial dissipation factor*
κ = *factor*
C_w = *the moisture content*

Experiments Test Matrix

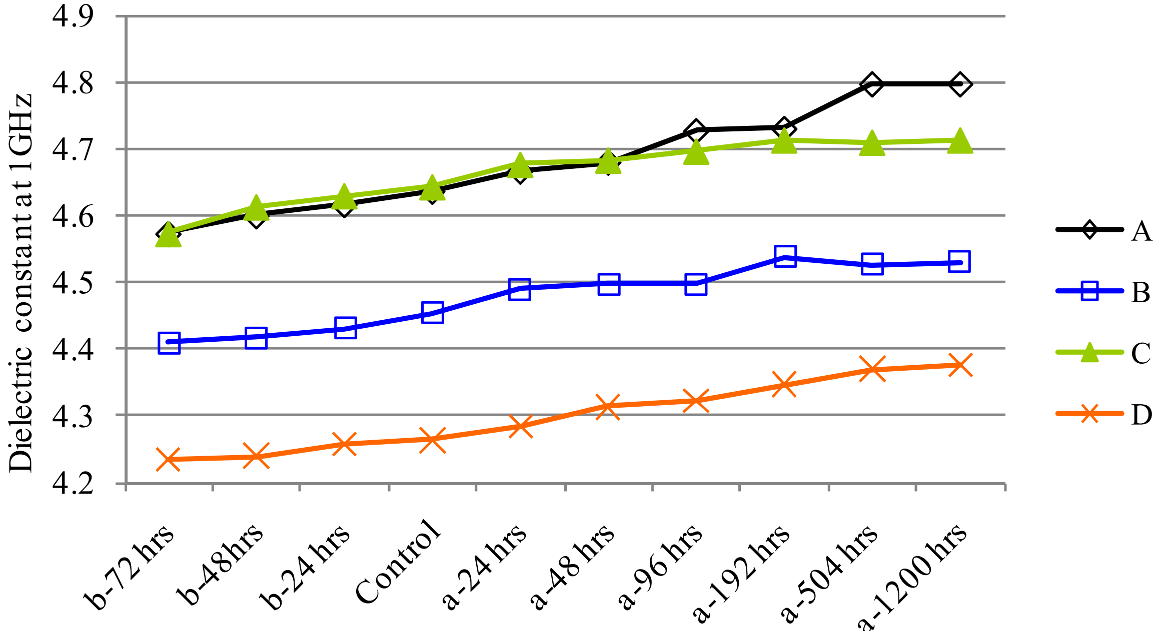


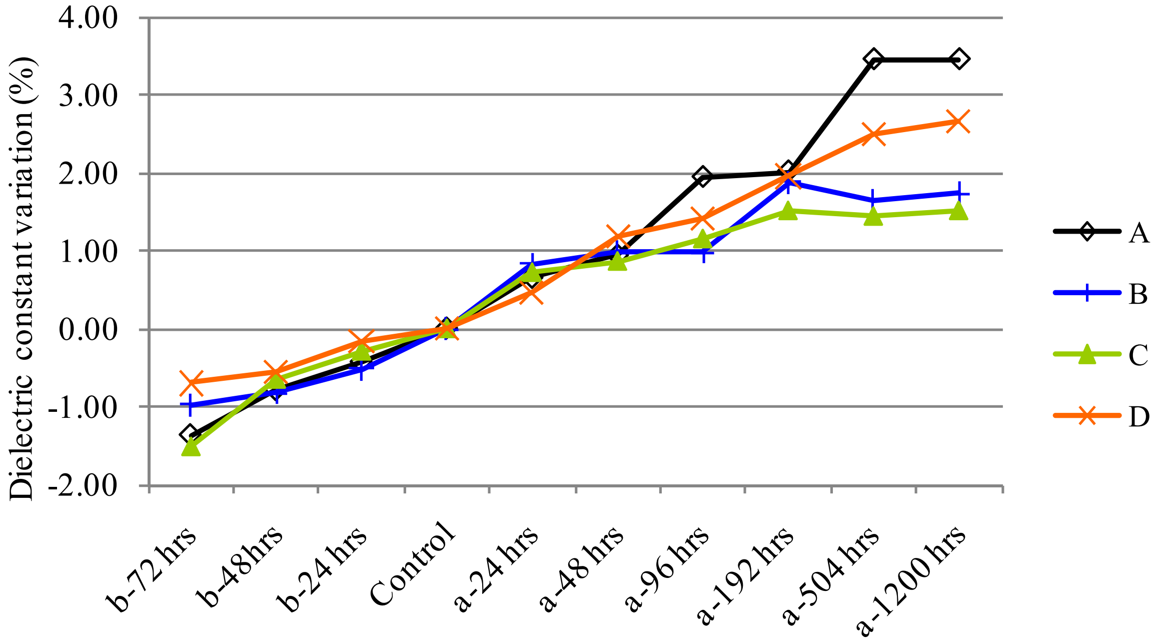
Laminates with Various Moisture Content Preconditioned by IPC-TM-650 2.5.5.9

Sets	Name	85ºC/ 85% RH (hrs)	105ºC (hrs)	23/50/24
Control	Control	-	2	√
Baking	b-24 hrs	-	24	√
	b-48 hrs	-	48	√
	b-72 hrs	-	72	√
Moisture absorption	a-24 hrs	24	2	√
	a-48 hrs	48	2	√
	a-96 hrs	96	2	√
	a-192 hrs	192	2	√
	a-504 hrs	504	2	√
	a-1200 hrs	1200	2	√

All materials are affected by moisture, including all reinforced laminates and most films. Therefore, all samples shall be conditioned at 23 ° C ± 2 ° C and 50% RH ± 5% RH for a minimum of 24 hours prior to testing. However, if a sample has recently been etched or exposed to excessive moisture, it should be dried in an air-circulating oven for two hours at 105 ° C +5 ° C, -2 ° C prior to testing and conditioned at room temperature as mentioned above.—IPC-TM-650 2.5.5.9

Dielectric Constant at 1GHz

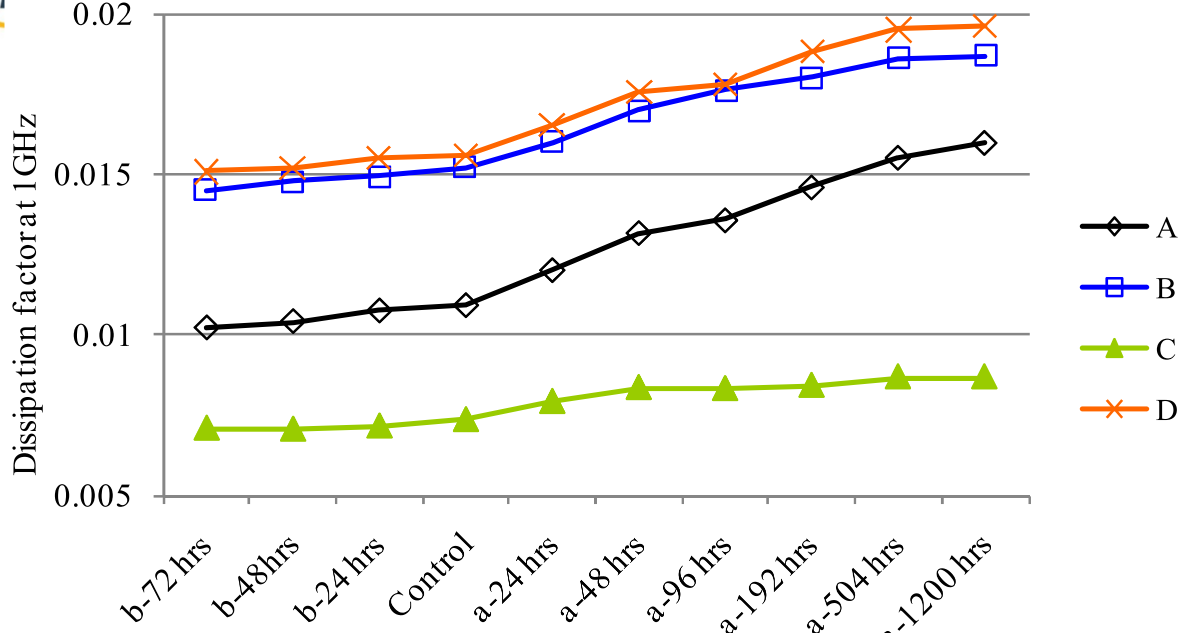


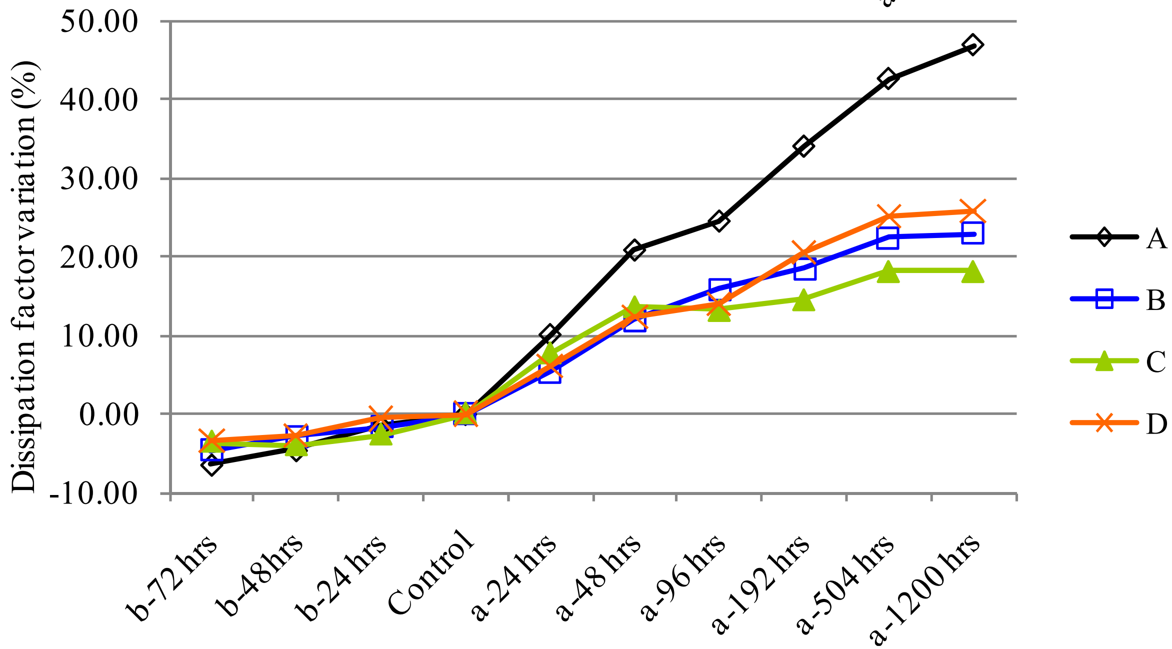


Baking for 2 hours can not get rid of majority moisture which laminate absorbed in 85/85.

The D_k still increased ~3.5 %

Dissipation Factor at 1GHz





D_f increased ~46.7% compared with the control set after preconditioned according to IPC test standard.

Preconditioning procedure outlined in IPC-TM-650 2.5.5.9 test standard can not account for different moisture content.

Summary

- Halogen-free laminates absorb more moisture under room storage conditions than halogenated materials.
- Exposure to humidity has an obvious impact on the laminate dielectric properties.
- The D_k and D_f increased linearly with an increase in the moisture content of the laminates. With specimen moisture content increasing from 0 to 0.98%, the D_k increased ~5.13% and the D_f increased ~74.5%.
- The preconditioning procedure outlined in the IPC-TM-650 2.5.5.9 test standard cannot account for different moisture content. Baking for 2 hrs cannot get rid of the majority of moisture. The D_k still increased ~3.5 % and the D_f increased ~46.7% compared with the control set after preconditioning according to the IPC-TM-650 2.5.5.9 test standard.

Back up

- The dielectric polarizations, which exist in the material, force the dielectric constant and dissipation factor of the insulating material to be a function of signal frequency.
- The two most important phenomena are dipole polarization due to polar molecules and interfacial polarization caused by inhomogeneities in the material. Thus moisture levels in PCB laminate significantly affect the electrical properties.
- The rate of polarization and movements of free ions/electrons are strong functions of testing temperature.
- Thus the electrical properties (D_k and D_f) of the insulating substrate of PCBs are functions of level of moisture, frequency and temperature [2].

D_k and D_f

Admittance of circuit (i):

$$Y = j\omega C = j\omega\varepsilon_r^{*}C_0$$

Complex Admittance of circuit (ii):

$$Y^{*} = G + j\omega C_p = j\omega\left(\frac{C_p}{C_0} - j\frac{G}{\omega C_0}\right)C_0$$

With the Complex permittivity defined as $\varepsilon_r^{*} = \varepsilon_r^{'} - j\varepsilon_r^{''}$

($\varepsilon_r^{'}$: Effective Relative Permittivity; $\varepsilon_r^{''}$: Relative Permittivity Loss)

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