Comparison of the Dielectric Constant and Dissipation Factors of non-woven Aramid/FR4 and Glass/FR4 Laminates

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Abstract
Permittivity and dissipation factor (D_k and D_f) are effects of polarization of different components of the dielectric substrate material when subjected to an electrical field. A database of these important design parameters for PWBs, has been developed for THERMOUNT® RT. Effects of variations in the level of moisture (bone dry to completely saturated at various relative humidity levels), testing temperature (room temperature to 120¡C) and testing frequencies (1 MHz to 1.5 GHz) on D_k and D_f are reported. As the frequency of test is increased from 1 MHz to 1.5 GHz, the effect of moisture on the properties are reduced. Comparison with conventional Glass/FR4 laminate properties shows distinct advantage of Thermount¤. It is increasingly used in high frequency cellular telephone, satellite, and wireless applications which require HDI PWBs to achieve the highest packaging density at the lowest cost and weight.

Introduction
The line spacing and the via-hole diameter, in printed wiring boards (PWBs), have been steadily shrinking with the push towards miniaturization of original equipment. High Density Interconnect (HDI) PWBs, utilizing 50-150 m blind micro-via-holes [1] are designed to meet these requirements. These types of PWB construction require stringent impedance control to optimize power input/output and noise control. Permittivity (D_k) and dissipation (loss tangent) factor (D_f) of the dielectric material significantly affect the impedance.

Permittivity and dissipation factor, of a dielectric material, are dependent on temperature, frequency of incoming signal and material content (e.g. moisture). The dielectric polarizations, which exist in the material, force the permittivity and the loss tangent factor of the insulating material to be a function of signal frequency[2]. The two most important phenomena are dipole polarization due to polar molecules and interfacial polarization caused by inhomogeneities in the material. Thus moisture level in a dielectric substrate will significantly affect the electrical properties. The permittivity is determined by an atomic or electronic polarization, at the highest frequency. The permittivity has its maximum value at zero frequency and each succeeding polarization, dipole or interfacial, adds its contribution to permittivity. Both loss tangent factor and dissipation factor exhibit a local maximum due to each polarization. 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 PWBs are functions of level of moisture, frequency and temperature.

In cellular phone applications, in particular, the design data requirements become very important because of their high transmission frequency and varied in-use environment (moisture and temperature).

The objective of this project was to compare the effects of the *testing environment* (moisture level of substrate, testing temperature and testing frequency) on the electrical properties of *dielectric substrates* (Glass/FR4 and aramid/ epoxy). The effect of frequency, moisture and temperature on D_k and D_f of aramid/epoxy (THERMOUNT) has been reported previously[3] . Comparative data of Glass/FR4 laminates under similar conditions will be reported here.

Scope:
Test: Microtek Laboratory conducted all the tests according to IPC-TM-650[4] method 2.5.5.4, using a Hewlett-Packard Impedance Analyzer 4291A. This instrument measures D_k and D_f reliably from 1 MHz to 1.5 GHz. To suit the objective of the test, we collected some extra data points (e.g. specimen weight before and after testing).

Material: We tested Thermount¤ and Glass/FR4 laminates under similar conditions. These laminates were acquired from commercial licensed vendors. Thermount¤ laminates were tested and data were reported previously. We retested few points as a control.

Thermount ¤ is laminate of epoxy and nonwoven aramid (100%) reinforcement. It is transversely isotropic in properties. From para-aramid and meta-aramid floc/binders, it begins as paper manufactured by Dupont. The nominal thickness of the 3.0N710 reinforcement is 0.0029" (72 μm). These are impregnated with high T_g epoxy in MEK solvent and laminated to a thickness of 0.06" (1.5 mm). The weight fraction of epoxy in laminates is ~ 53%. Two laminators (material A and B), from the USA, provided the laminates.

Glass/FR4 laminate was acquired from one of the above laminators, with ~50% (high Tg) epoxy content. These laminates were made from standard plies of 7628 E-glass.

Moisture Absorption: According to standard procedure[2], all the specimens were brought to "bone-dry" conditions and weighed. Sets of "bone-dry" specimens, were exposed to humidity, at 85 °C. Six (6) specimens from each set were measured for weight gain, at 24 hours intervals[5]. When the average weight gain, of the last three (3) measurements, was less than 1% of the total weight gain (for each specimen), the set was considered "fully saturated".

Glass/FR4 laminates were exposed only 85% RH and the THERMOUNT specimens were exposed to 55%, 70% and 85% RH.

The following effects were considered:

1) Effect of TEST TEMPERATURE on D_k and D_f of saturated and "bone-dry" laminates.

We measured D_k and D_f at 25, 80 and 120 °C. The THERMOUNT specimens were tested at four levels of moisture - bone-dry and fully saturated at 85% RH, 70% RH and 55% RH. The testing frequency was 1 MHz.

Glass/FR4 laminates were tested under similar conditions. In this case we only tested "bone-dried" specimens and specimens saturated at 85% RH.

2) Effect of TESTING FREQUENCY on D_k and D_f

We measured D_k and D_f at 1 MHz, 10 MHz, 100 MHz, 1 GHz and 1.5 GHz. Both glass/FR4 and THERMOUNT specimens were tested at two (2) levels of moisture - bone-dry and fully saturated at 85% RH (maximum moisture content). The testing temperature, for this set was 25 °C.

3) Effect of SATURATION LEVEL on D_k and D_f

THERMOUNT specimens were exposed to 85% RH at 85°C for different lengths of time to absorb approximately 25%, 50% and 75% of total saturation level of moisture. We measured D_k and D_f at five (5) moisture levels: "bone-dry", "fully saturated", 25%, 50% and 75% (of fully saturated). Tests were conducted at 25°C and 1 MHz.

Glass/FR4 laminates were not tested for these "partial saturated" conditions.

Experimental Details:
In general, ASTM D 150 (IPC-TM-650 method 2.5.5.3) was followed. Three (3) specimens were tested from each material group (Thermount A & B and Glass/FR4) for each test.

The specimens were taken out of the "humidity chamber", cooled, weighed and placed in the analyzer (HP 4291A). Specimens were allowed to stabilize in the machine for 2 - 5 minutes. After stabilization and testing, the specimens were cooled and weighed again. The maximum difference between "before" and "after" moisture content was ~0.06% (negligible). The average of these two weights, before and after test, is used for calculating (table 1) the moisture content of a specimen during the test.

Discussion of Results:
The differences of measured values of electrical properties (D_k and D_f) for different lots of THERMOUNT and different specimens (within a test condition) were negligible. The data for THERMOUNT, as reported in table 1 and in all the figures (1 - 5), are averages of six (6) specimens. The data for Glass/FR4 represent averages of three (3) specimens (single lot).

Moisture absorption: The moisture absorption by the composite laminates is graphically displayed in figure 1. The exposure started with bone-dry specimens. As received, the THERMOUNT specimens had average moisture content of 0.66%. The maximum moisture absorbed (saturated) by the THERMOUNT laminates was 1.89 % (material A, 85% RH). Material A absorbed more moisture at all the humidity levels. However, for all the tests, there was no significant difference within batch and between batches. We reported average of six values (3 specimens/2 types of materials).

Glass/FR4 laminates had an average 0.07% as received moisture. At 85°C and 85% RH exposure level, the saturation moisture content was 0.7%

Effect of Testing Temperature: The dielectric constant (D_k), increases with increase in testing temperature (figure 2). As the testing temperature increased from 25°C to 120°C, D_k increased by ~10%, for THERMOUNT. D_k increases non-linearly and monotonically as a function of the temperature. Glass/FR4 laminates followed the same pattern.

The dissipation factor (D_f), in general, decreases with increase in testing temperature (figure 3). D_f decreases non-linearly and monotonically as a function of the temperature, for THERMOUNT and glass/FR4 laminates.

Effect of Specimen Moisture content: Exposure to different relative humidity levels (85%, 70% and 55%) at 85°C and "bone-dry" conditions produced different moisture levels in THERMOUUNT laminates. Glass/FR4 laminates were only tested at "bone-dry" condition and saturated at 85% RH. The dielectric constant (D_k) increased with increase in moisture content (figure 2). For THERMOUNT, with specimen moisture content increasing from 0% to 1.9%, the D_k increased ~19% (maximum). The Glass/FR4 laminate had a maximum moisture content of 0.7% and the D_k increased ~12%.

The dissipation factor (D_f), in general, also increases with increase in moisture content (figure 3), for both glass/FR4 and THERMOUNT. The magnitude of change is similar for both the types of substrates.

Effect of Testing Frequency: Five (5) frequencies, from 1 MHz to 1.5 GHz, were selected for this test. Specimens were tested in the same tester (HP4291A) for the range of frequencies. The tests were conducted on bone dry specimens and specimens saturated with moisture at 85 % RH. The testing temperature was 25°C for all the tests.

The dielectric constant (D_k), in general, decreased with increase in test frequency (figure 4). With testing frequency increasing from 1 MHz to 1.5 GHz, the D_k decreased for both glass/FR4 and THERMOUNT. However, as the frequency increased, the effect of moisture (bone dry to saturated at 85% RH) on D_k decreased, more noticeably for THERMOUNT. For all the frequencies, D_k of THERMOUNT was significantly lower than that of glass/FR4.

The dissipation factor (D_f) for THERMOUNT, in general, remained constant with increase in test frequency up to 100 MHz (figure 5). At 1.5 GHz, we see a decrease in D_f. The D_f is a non-linear function of frequency, with a possible local maximum at 500 MHz - 1GHz. Thus at a very high frequency (>1.5 GHz), Df of THERMOUNT laminates will decrease with increase in frequency.

The dissipation factor (D_f) for glass/FR4, in general, decreased with increase in test frequency up to 100 MHz (figure 5). At that point it reached a local minimum and D_f started to increase with increase in frequency (500 MHz - 1.5 GHz). Thus at a very high frequency (>1.5 GHz), D_f of glass/FR4 laminates will increase with increase in frequency.

Summary

We have measured the effect of changes in temperature, frequency and moisture content on the dielectric constant and dissipation factor of PWB laminates constructed from composite of aramid/ epoxy resin and glass/FR4.

We found that the properties of THERMOUNT were statistically equivalent within and between batches of specimens from two laminators) . The results are reported as an average of six specimens. The maximum moisture absorption was ~2% at saturation (85% RH). The maximum moisture absorption for glass/FR4 laminate was ~0.7% at saturation (85% RH).

The D_k of the substrates increased monotonically with increase in the temperature and the moisture content of the specimen. Increase in frequency decreased the D_k of the substrate, following a log-linear function.

The dielectric constant (D_k) of the aramid/epoxy laminate varied from 3.4 to 4.8, due to simultaneous wide variations in *moisture content* (0% to 2%), testing *temperature* (25 °C to 120 °C) and testing *frequency* (1 MHz to 1.5 GHz). The increase of D_k, due to increase in moisture content, is reduced as the frequency increased.

The dielectric constant (D_k) of the glass/FR4 laminate varied from 4.5 to 5.8, due to simultaneous wide variations in testing *temperature* (25 °C to 120 °C) and testing *frequency* (1 MHz to 1.5 GHz). The D_k of glass/FR4 was significantly higher than that of THERMOUNT laminate under every condition.

We found that, the D_f of the substrate decreased with increase in the test temperature. The D_f of the substrate increased with the moisture content of the specimen. Increase in test frequency decreased the D_f of the THERMOUNT after 100 MHz, displaying a possible local *maximum* at 500 MHz - 1GHz. Increase in test frequency increased the D_f of the glass/FR4 after 100 MHz, displaying a possible local *minimum* at 500 MHz - 1GHz

The laminates, from THERMOUNT®-RT™ prepregs and glass/FR4 showed similar behavior under different testing conditions. The effect of moisture on the electrical properties of THERMOUNT reduced as the testing frequency increased to GHz range. Thus for cellular phones, where light weight and performance at high frequency are very important, THERMOUNT can provide significant improved value-in-use.

Acknowledgement:

I would like to thank Arlon Material for Electronics and Nelco International Corporation for providing the laminates for test. I extend my gratitude towards my teammates at DuPont Advanced Fibers Systems for their active and continuous support of the project.

References:

[1] High Speed Laser Ablation of Microvia Holes in Nonwoven Aramid Reinforced Printed Wiring

Boards to Reduce Cost , IPC Expo 96 Technical Conference, San Jose, CA, February 1996, David J. Powell and Michael Weinhold, DuPont AFS.

[2] ASTM Test Method D 150 - "AC Loss Characteristics and Permittivity (Dielectric Constant) of Solid Electrical Insulation" *Annual Book of ASTM Standards*, American Society for Testing and Materials, West Conshohocken, PA

[3] Effect of Moisture and Temperature on the Dielectric Constant and Dissipation Factor of HDI PWBs containing non-woven Aramid Laminate and Prepreg , IPC Expo 99 Technical Conference, Long Beach, CA, March 99, Subhotosh Khan,DuPont AFS

[4] IPC_TM_650 Method 2.5.5.4 - "Dielectric Constant and Dissipation Factor of Printed Wiring Board Material - Micrometer Method" *IPC Test Methods Manual: IPC-TM-650*, The Institute for Interconnecting and Packaging Electronic Circuits, 2215 Sanders Rd., IL

[5] MIL-HDBK-17-1E "Moisture absorption and conditioning factors", *Polymer Matrix Composites*, Vol. 1, section 2.2.7, pp. 2-19, Department of Defense Handbook, DODSSP

[6] New Applications for Nonwoven Aramid Reinforcement Which Demand Advanced Physical Properties , IPC Expo 97 Technical Conference, San Jose, CA, March 1997, Birol Kirayoglu, David J. Powell and Michael Weinhold, DuPont AFS.

Table 1: Averaged Specimen Data for D_k and D_f at different Testing conditions
(PWB laminates with aramid paper - 3N710/epoxy - 47/53 - 0.06" thick)

Test#	Humidity (% RH)	Saturation level (%)	Frequency (MHz)	Temperature (°C)	Average Moisture		Average D_k		Average D_f	
					FR4/Glass	Thermount	FR4/Glass	Thermount	FR4/Glass	Thermount
1	0	0	1	25	0.01%	0.00%	4.83	3.79	0.015	0.014
1	0	0	1	80	0.00%	0.00%	5.09	3.95	0.009	0.007
1	0	0	1	120	0.00%	-0.01%	5.20	4.04	0.009	0.005
2	0	0	10	25	0.00%	0.00%	4.69	3.67	0.012	0.016
2	0	0	100	25	0.01%	0.00%	4.59	3.51	0.011	0.018
2	0	0	1000	25	0.00%	0.00%	4.52	3.43	0.010	0.018
2	0	0	1500	25	0.00%	0.00%	4.68	3.37	0.018	0.009
1	85	100	1	25	0.68%	1.94%	5.38	4.38	0.020	0.024
1	85	100	1	80	0.66%	1.89%	5.61	4.68	0.019	0.016
1	85	100	1	120	0.62%	1.85%	5.82	4.80	0.014	0.015
2	85	100	10	25	0.66%	1.90%	5.15	4.18	0.018	0.026
2	85	100	100	25	0.64%	1.88%	4.90	3.93	0.014	0.026
2	85	100	1000	25	0.67%	1.90%	4.75	3.72	0.016	0.027
2	85	100	1500	25	0.66%	1.88%	4.78	3.73	0.017	0.021
3	85	25	1	25		0.52%		3.94		0.016
3	85	50	1	25		0.98%		4.01		0.019
3	85	75	1	25		1.43%		4.11		0.021
1	55	100	1	25		1.25%		4.13		0.021
1	55	100	1	80		1.22%		4.42		0.014
1	55	100	1	120		1.20%		4.54		0.012
1	70	100	1	25		1.62%		4.23		0.022
1	70	100	1	80		1.58%		4.56		0.016
1	70	100	1	120		1.55%		4.66		0.015

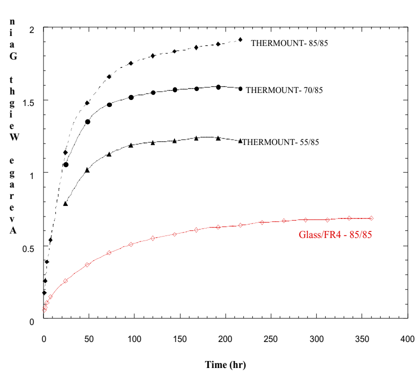

Figure 1 Rate of Moisture absorption of laminates at 85° C and different RH (Glass/FR4 & 3N710/epoxy - 47/53 - 0.06" thick)

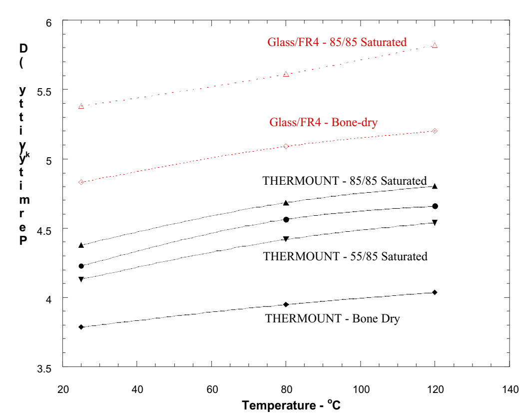

Figure 2 *Dielectric Constant* as a function of testing *temperature* (Glass/FR4 & 3N710/ epoxy - 47/53 - 0.06" thick, Testing Frequency 1 MHz)

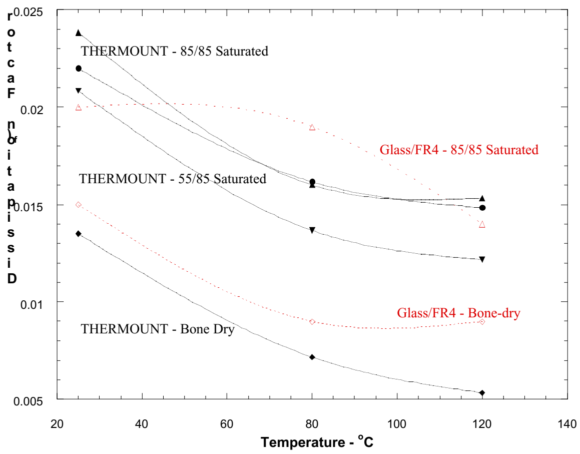

Figure 3 *Dissipation Factor* as a function of testing *temperature* (Glass/FR4 & 3N710/ epoxy - 47/53 - 0.06" thick, Testing Frequency 1 MHz)

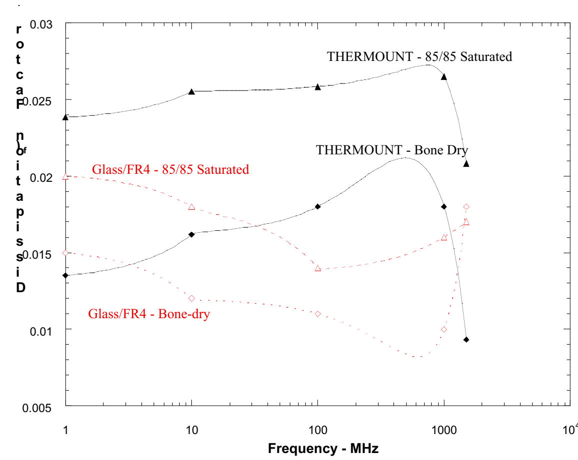

Figure 5 *Dissipation Factor* as a function of testing *frequency* (Glass/FR4 & 3N710/ epoxy - 47/53 - 0.06" thick, Testing Temperature 25°C)

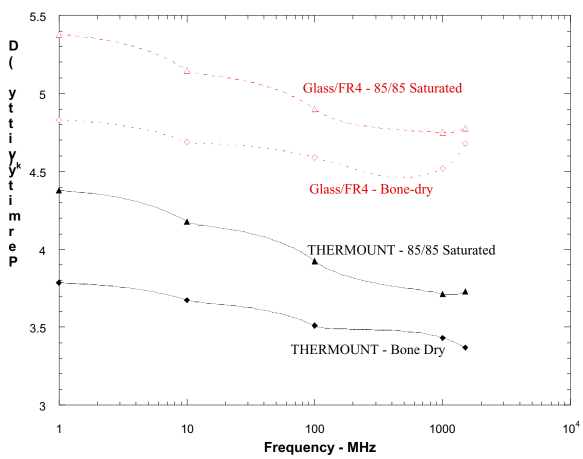

Figure 4 *Dielectric Constant* as a function of testing *frequency* (Glass/FR4 & 3N710/ epoxy - 47/53 - 0.06" thick, Testing Temperature 25°C)

Comparison of the Effects of Moisture, Temperature and Frequency on D_k and D_f of THERMOUNT® Aramid/FR4 and Glass/FR4 Laminates

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What Is THERMOUNT¤ - RT“ ?

- Laminate and prepreg which contains DuPont type N710 nonwoven 100% aramid reinforcement and high Tg epoxy resin for use in printed wiring boards, MCM-Ls, and semiconductor chip carrier packages

- Primary ingredient is a highly oriented p-aramid (p-phenylene terephthalamide) short fiber, randomly distributed in a thin sheet structure

- Dupont nonwoven aramid reinforcement is formed in specialized paper making equipment using a unique m-aramid binder, and densified to a precise thickness

Key Characteristics of THERMOUNT¤ - RT“

- Controlled in-plane CTE
- Dimensional stability
- Light weight
- Smooth, thin dielectric
- Uniform thickness
- Low dielectric constant
- High speed Laser processable

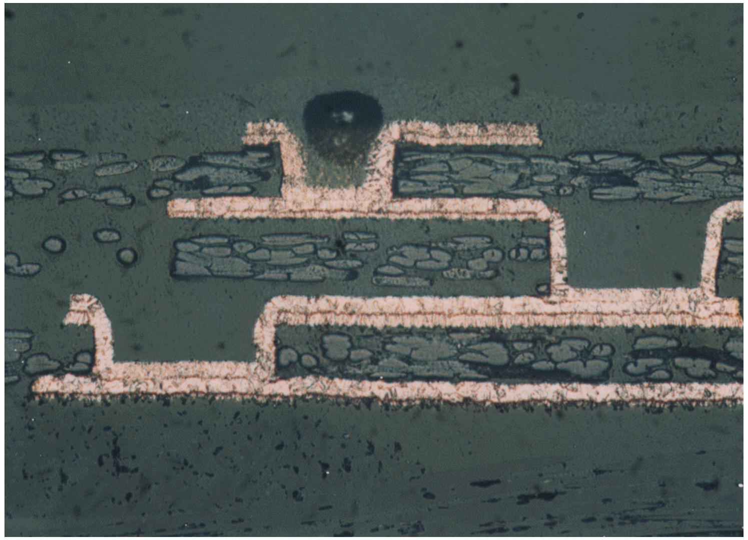


Photo courtesy of Siemens AG, Germany

Test Objective

Effect of Moisture Content and Test Temperature

- **Vary Moisture content by using**
  - Bone dry specimens
  - Fully saturated specimens at
    - 85% RH
    - 70% RH
    - 55% RH
  - Partially saturated (25%, 50 % and 75%) at 85% RH
- **Testing Temperatures**
  - 25 ^{o}C (bone dry, fully saturated and partially saturated)
  - 80 ^{o}C (bone dry, fully saturated)
  - 120 ^{o}C (bone dry, fully saturated)
- **Testing Frequency**
  - 1 MHz

Test Objective

Effect of Testing Frequency

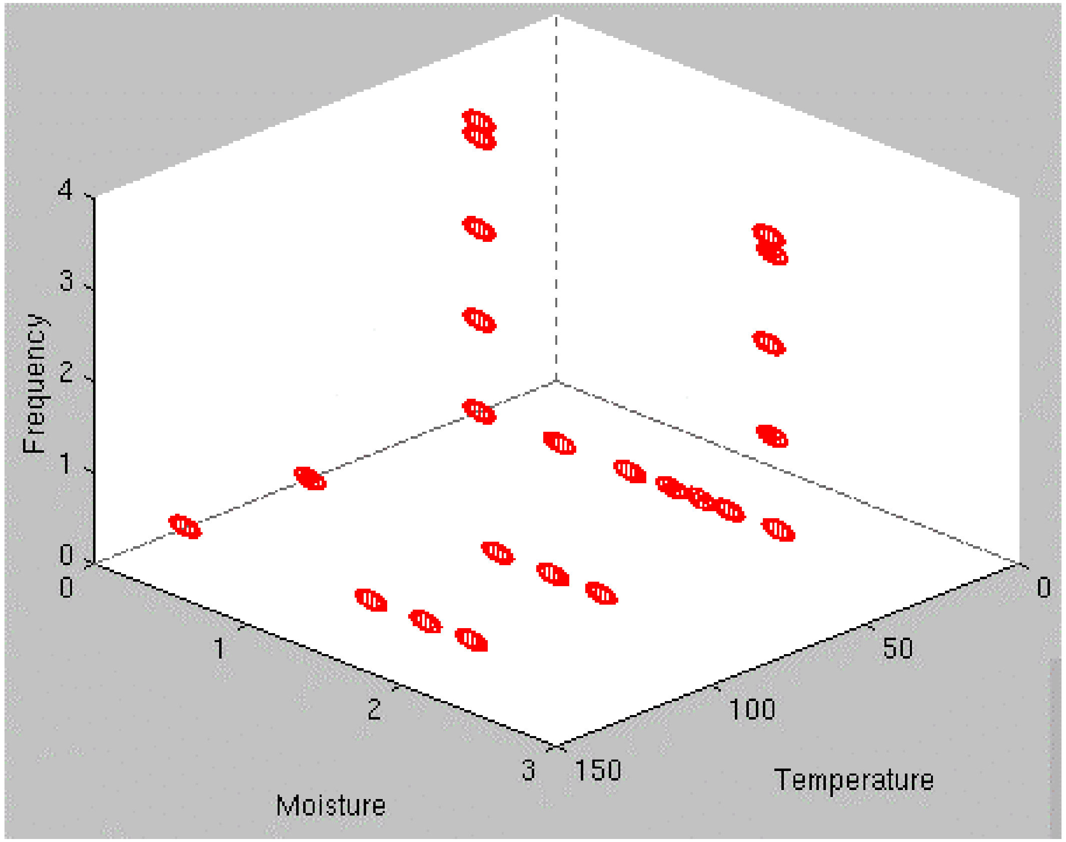
- **Test at Following Frequencies**
  - 1 MHz
  - 10 MHz
  - 100 MHz
  - 1000 MHz (1 GHz)
  - 1500 MHz
- **Vary moisture content by using**
  - Bone dry specimens
  - Fully saturated specimens at 85% RH
- **Testing Temperatures**
  - 25 ^{o}C (bone dry, fully saturated and partially saturated)

Test Objective

Material

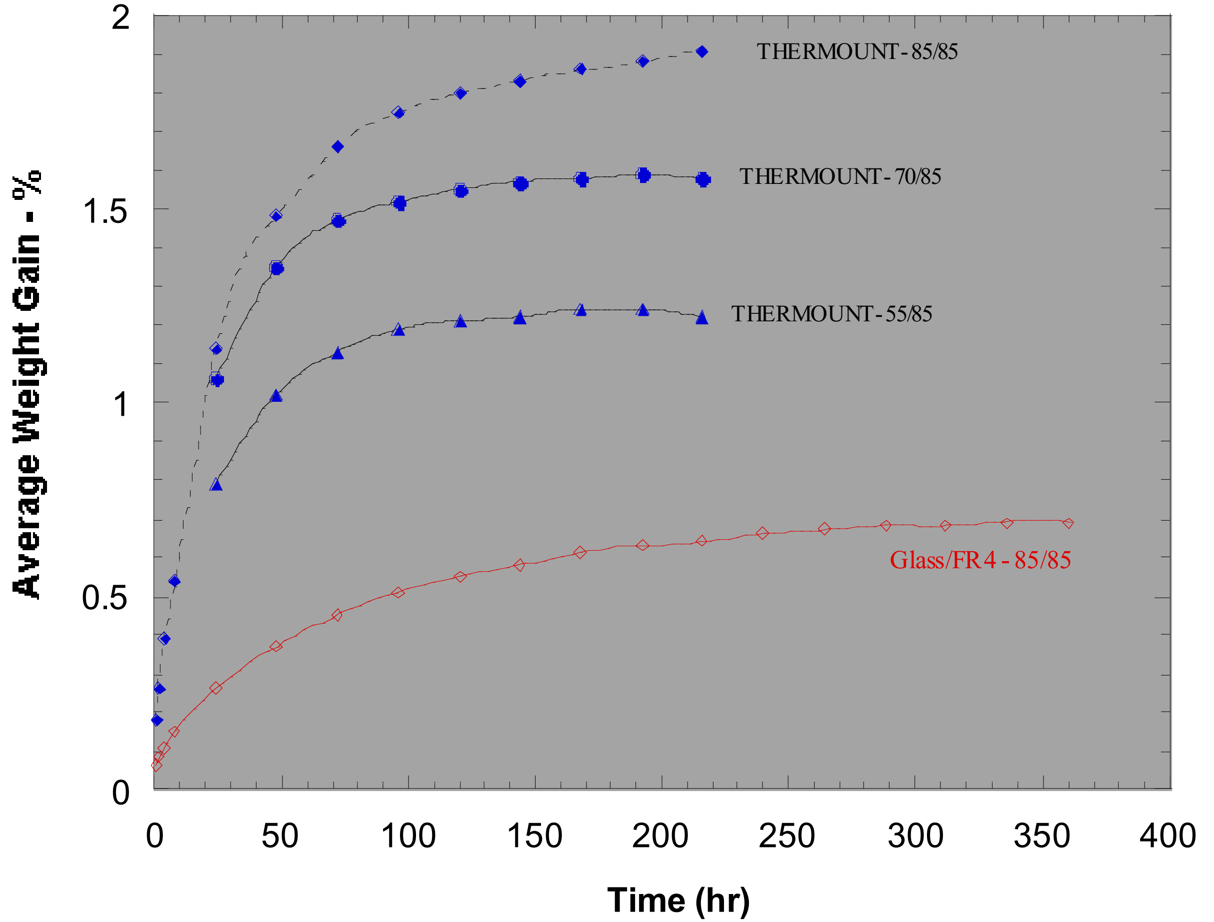
- **THERMOUNT¤ - RT“ Laminates**
  - ➔ Nominal Paper Thickness 3 mils (72 µm)
  - ➔ High Tg epoxy (160 ^{o}C) - MEK solvent
  - ➔ 53 – 3 % W_f epoxy in cured laminate
  - ➔ Nominal Laminate thickness 60 mils (1.5 mm)
- Standard E-glass type 7628 - 7 + 2 plies (~50% epoxy)
- **Two Licensed Vendor supplied Laminates**
  - ➔ Vendor A (Material A-aramid) and Glass/FR4
  - ➔ Vendor B (Material B-aramid)
- **Testing Procedure**
  - ➔ IPC - TM - 650 2.5.5.4 (ASTM D 150) using HP 4291A
  - ➔ Tested at Microtek Laboratories

Test Domain



- Test points are shown in the Temperature-Moisture content-Frequency space
- The origin is into the plane of paper (center of hexagon)- frequency is in Log (MHz) scale
- At each point, six (6) Thermount/FR4 were tested
- Three (3) glass/FR4 specimens were tested at some of the points.

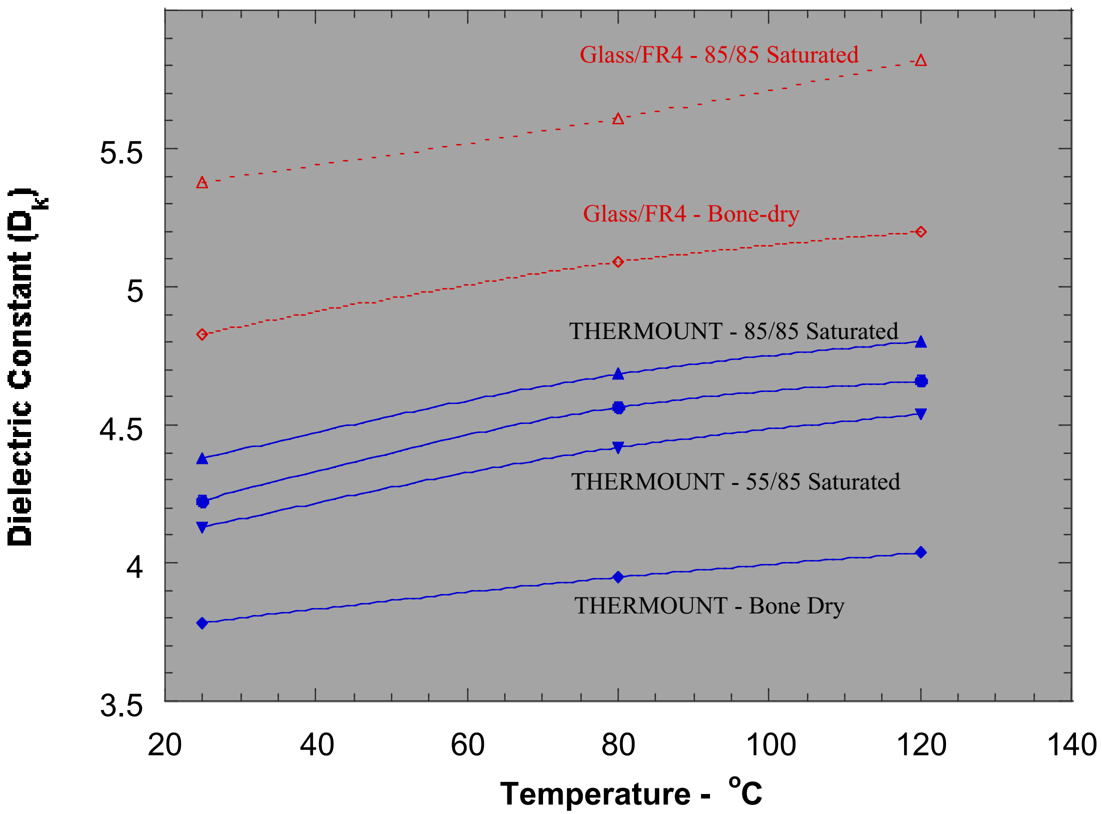
Rate of Moisture Absorption



¥ At 85°C/85%RH, the saturated moisture content of Thermount/FR4 laminate < 2%

¥ At 85°C/85%RH, the saturated moisture content of Glass/FR4 laminate < 0.7%

Effect of Test Temperature on D_k



¥ D_k of Thermount/FR4 and Glass/FR4 increased with increase in test temperature

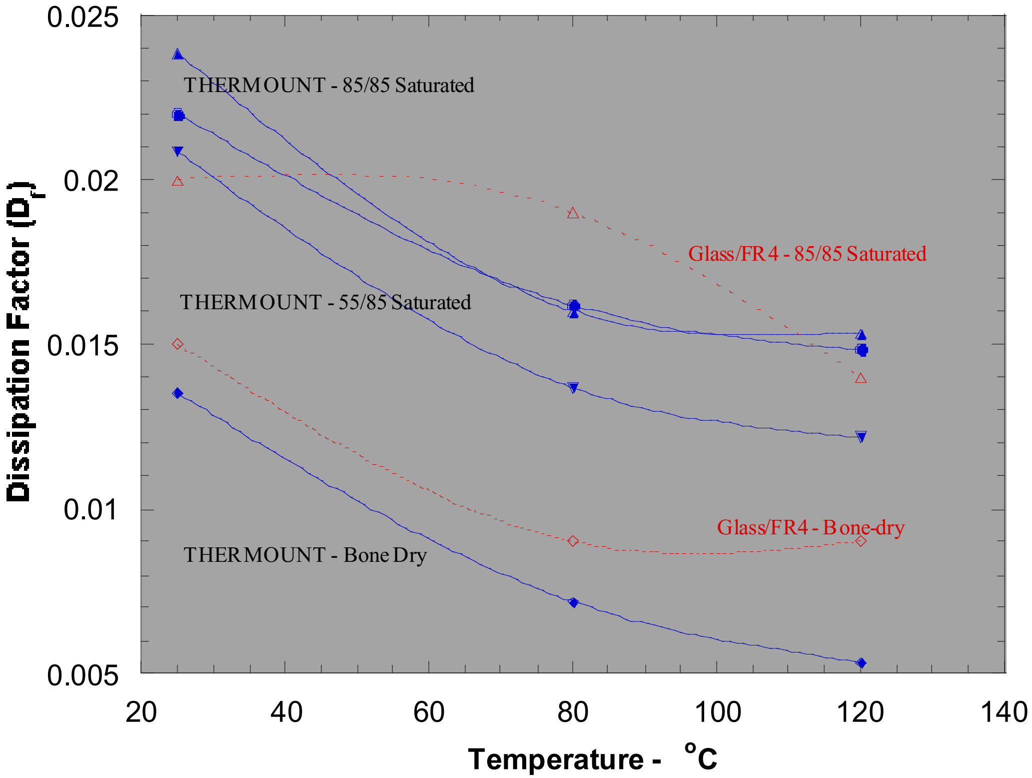
¥ The increase in D_k due to full saturation is same for Glass/FR4 and Thermount /FR4 (=~0.6)

¥ D_k of Glass/FR4 changes from 4.8 to 5.8 due to changes in temperature and moisture

¥ D_k of Thermount/FR4 changes from 3.8 to 4.7 due to changes in temperature and moisture

¥ Thermount/FR4 has a **lower** D_k than Glass/FR4 under **ALL** conditions tested.

Effect of Test Temperature on D_f

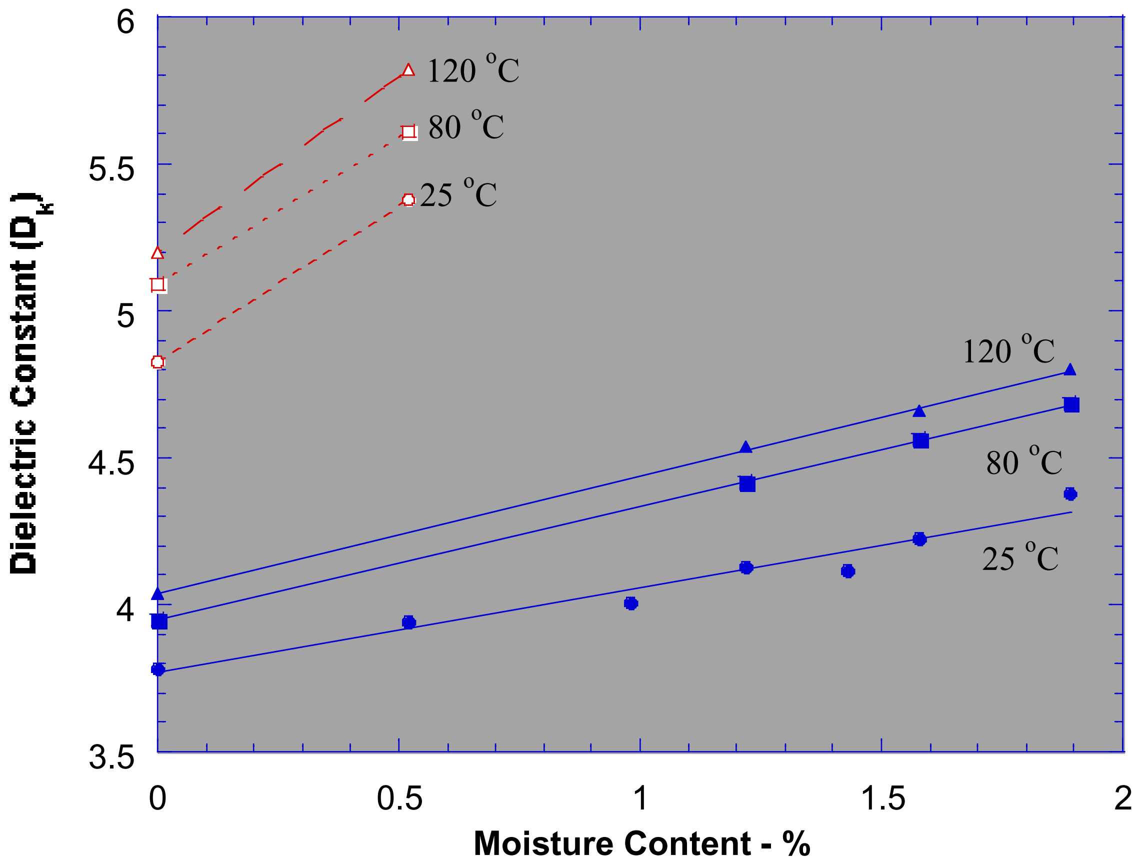


¥ D_f of Thermount **decreases** with increase in temperature - but **increases** with increase in moisture

¥ D_f of Glass/FR4 goes through **extremum** at ~80 oC (fitted with cubic spline)

¥ D_f of Thermount/FR4 is less than or equal to Glass/FR4 under all the conditions tested

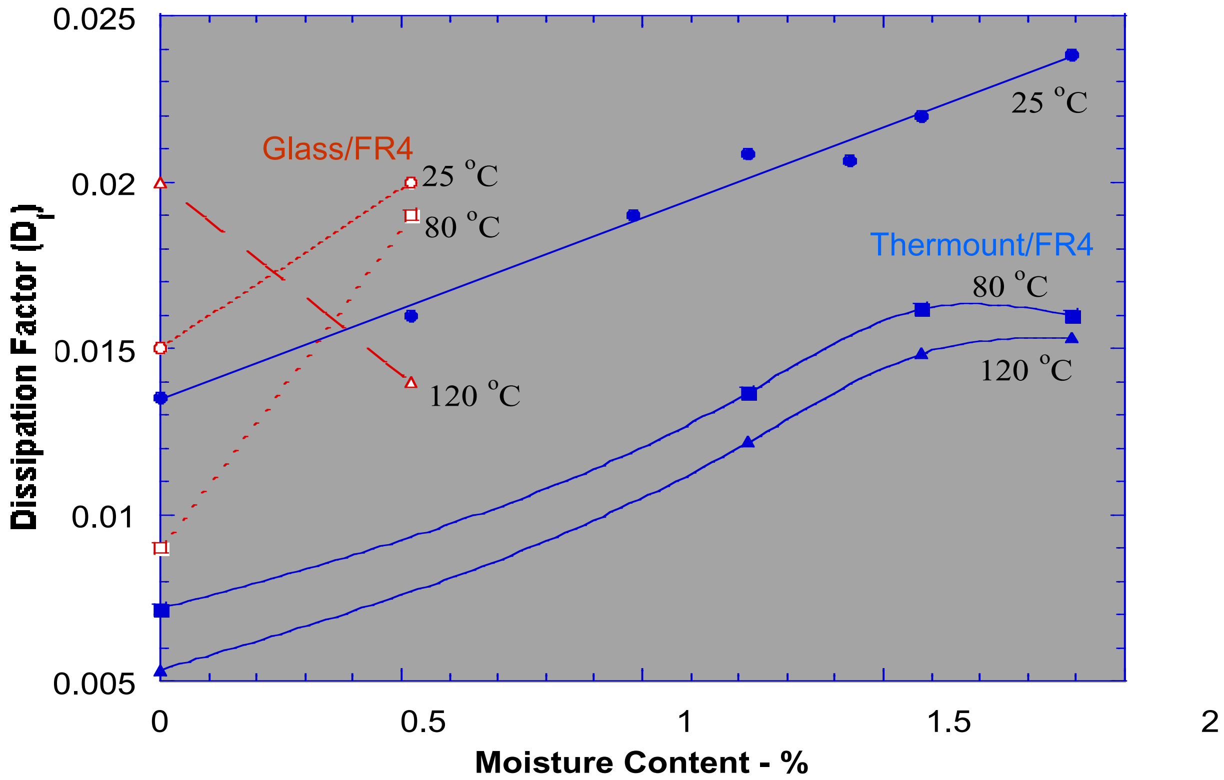
Effect of Moisture Content on D_k



¥ D_k of Thermount/FR4 increases linearly with increase in moisture

¥ D_k of Thermount/FR4 is **lower** than that of Glass/FR4 under all testing conditions

Effect of Moisture Content on D_f

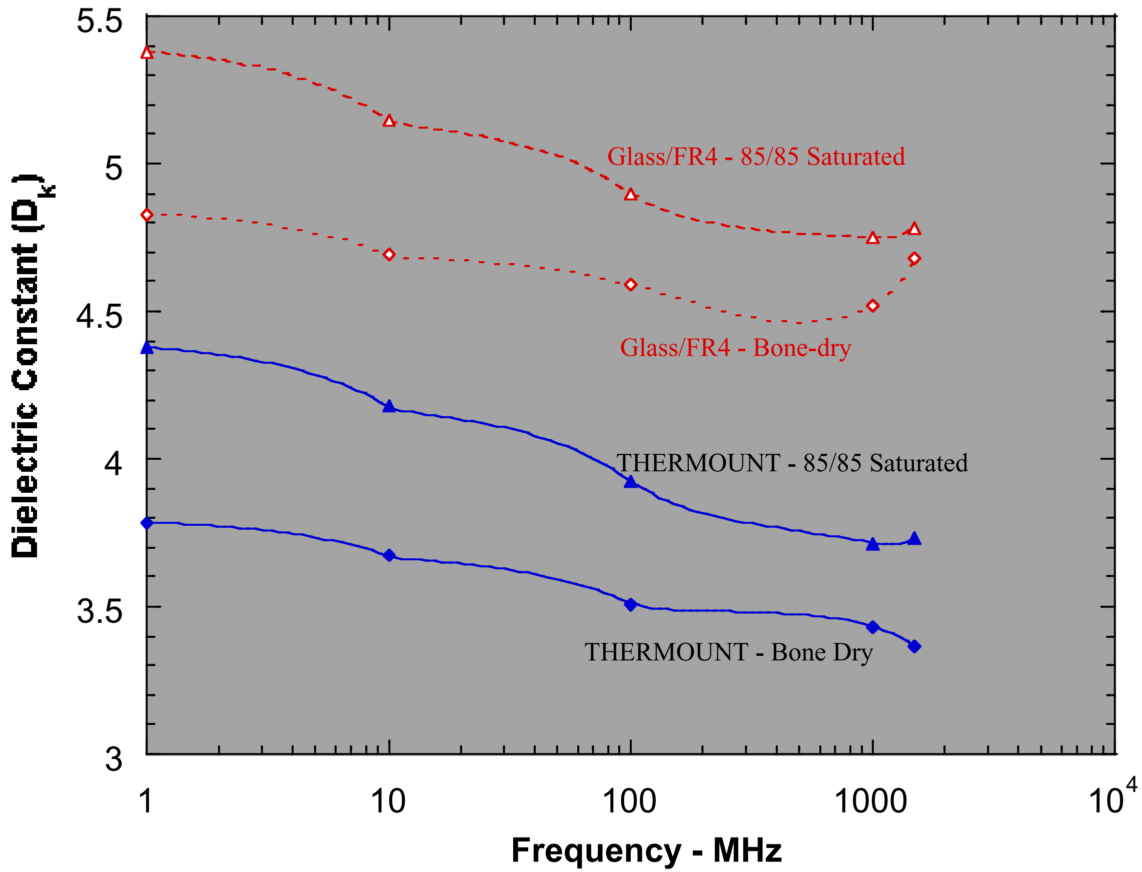


¥ D_f of Thermount/FR4 generally increased with increase in moisture content

¥ D_f of Glass/FR4 generally increased with increase in moisture content

¥ D_f of Glass/FR4 is generally **higher** than that of Thermount/FR4 under similar testing condition

Effect of Testing Frequency on D_k

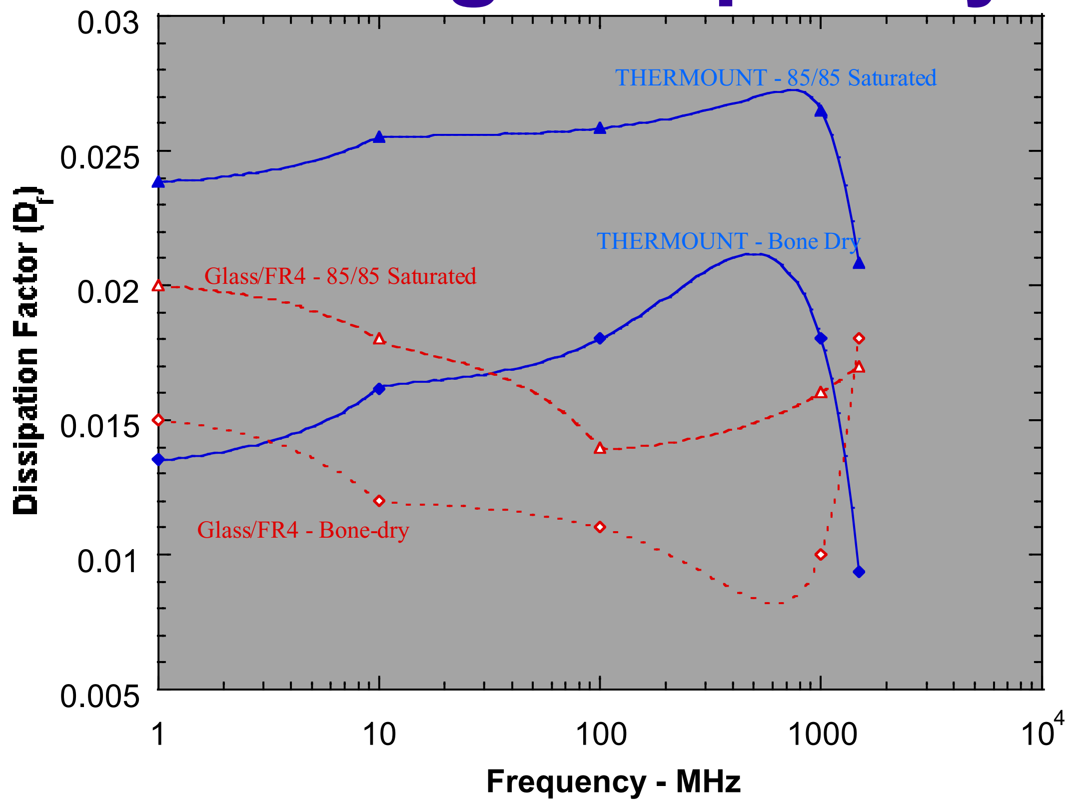


¥ D_k of Thermount/FR4 decreases with increase in test frequency

¥ D_k of Glass/FR4 may increase with increase in frequency beyond 1 GHz

¥Effect of moisture content on D_k **decreases** with increase in frequency

Effect of Testing Frequency on D_f



¥ D_f of Thermount/FR4 reaches a maximum at ~ 500 MHz

¥ D_f of Glass/FR4 reaches a minimum at ~ 500 MHz - D_f increases beyond this point with increase in frequency

¥Effect of moisture content on D_f **decreases** with increase in testing frequency

¥ Presence of extrema in these plots indicate change in polarization mechanism - from moisture (dipolar) to ionic

Summary

- Laminates of THERMOUNT¤ RT" (nonwoven aramid reinforcement / high Tg epoxy resin) and Glass/FR- 4 behave predictably under variable moisture content, frequency and testing temperature.
- Laminates from two vendors exhibited statistically equivalent properties for aramids.
- Under widely varying testing conditions, D_k varied from 3.4 to 4.8 for aramid/epoxy and 4.5 to 5.8 for glass/epoxy .
- D_f varied from 0.005 to 0.03 for aramid/epoxy and 0.01 to 0.02 for glass/epoxy.
- Maximum moisture intake was 1.99% (< 2%) for aramid/epoxy.
- Increasing moisture content increases both D_k and D_f.
- Increasing temperature increased D_k but decreased D_f.
- Increasing frequency decreased D_k. D_f went through a local maximum/minimum.
- Effect of moisture decreases with increase in frequency.